NOAA TECHNICAL MEMORANDUM NWS NSSFC-1

D

NEW SEVERE THUNDERSTORM RADAR IDENTIFICATION TECHNIQUES AND WARNING CRITERIA: A PRELIMINARY REPORT

Leslie R. Lemon
Techniques Development Unit
National Severe Storms Forecast Center
Kansas City, Missouri

July 1977

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Weather Service

NOAA TECHNICAL MEMORANDA

National Weather Service
National Severe Storms Forecast Center Subseries

The National Severe Storms Forecast Center (NSSFC) has the responsibility for the issuance of severe thunderstorm and tornado watches for the contiguous 48 states. Watches are issued for those areas where thunderstorms are forecast to produce one or more of the following: (1) hailstones of 3/4-inch diameter or greater, (2) surface wind gusts of 50 knots or greater, or (3) tornadoes.

NOAA Technical Memoranda in the NWS, NSSFC subseries are produced under the technical guidance of the NSSFC, Techniques Development Unit. They facilitate rapid dissemination of material of general interest in the field of severe storm meteorology. These papers may be preliminary in nature, and may be formally published elsewhere at a later date.

These papers are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, Sills Building, 5285 Port Royal Road, Springfield, Virginia 22151. Price is $3.00 per copy, $1.45 for microfiche.

NOAA TECHNICAL MEMORANDUM NWS NSSFC-1

NEW SEVERE THUNDERSTORM RADAR IDENTIFICATION TECHNIQUES AND WARNING CRITERIA: A PRELIMINARY REPORT

Leslie R. Lemon
Techniques Development Unit
National Severe Storms Forecast Center
Kansas City, Missouri

July 1977

UNITED STATES
DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

National Weather
Service
George P. Cressman, Director

TABLE OF CONTENTS

NEW SEVERE THUNDERSTORM RADAR IDENTIFICATION TECHNIQUES AND WARNING CRITERIA: A PRELIMINARY REPORT

Leslie R. Lemon
Techniques Development Unit, National Severe Storms Forecast Center
NOAA, Kansas City, Missouri

ABSTRACT

Improved understanding of severe thunderstorm structure and evolution is used to develop new radar sampling techniques and warning criteria. The only radar data needed are obtained from the conventional National Weather Service radars (WSR-57, WSR-74C and S) when in PPI tilt sequence mode displaying video integrated and processed reflectivities. Actual WSR-57 data for six storms are used to exemplify the techniques and criteria.

1. INTRODUCTION

Worldwide research has been done on convective storm structure and evolution since 1960. Data sources have included volunteer observer networks, special surface and upper air networks, aircraft and high resolution conventional and Doppler radar. Through synthesis of these data much has been learned about the characteristics of severe thunderstorms.

Concurrently, new technological developments have allowed production of advanced radar data processing and display systems. While some of the new radar display technology has been implemented in the operational community (e.g., the video integrator and processor, VIP), little of the increased understanding of storm structure has influenced severe thunderstorm radar recognition techniques or warning criteria.

This report and one by Lemon (1977) present results of a continuing study designed to improve conventional radar sampling and severe storm identification methods in the National Weather Service. Since a severe storm's physical structure is important to its characteristics, as depicted by radar, a general discussion of that structure is presented. It is hoped that this presentation will help the weather radar specialist and forecaster use the VIP WSR-57 and WSR-74C and S radar data to recognize the incipient severe thunderstorm more effectively and to issue timelier warnings.

2. THE SUPERCELL STORM

Several categories of thunderstorms such as squall lines, multicell, supercell, and severely sheared storms have been identified (Marwitz, 1972a,b,c; Chisholm, 1973). The squall line can be composed of either (or both) multicell or supercell storms although the former is predominant. The severely sheared storm is a subset of the supercell. Thus, the most basic storm types are the multicell and supercell storms. The majority of thunderstorms fall into the nonsevere multicell category and consist of a series of cells or several coexisting cells, each of which goes through the familiar updraft-downdraft life cycle described by Byers and Braham (1949).

A relatively small, but quite significant, number of thunderstorms are characterized by a single persistent cell which generally travels appreciably to the right (occasionally left) of the winds. These so-called supercell storms exhibit a radar identifiable structure with the updraft and downdraft coexisting for periods which are long compared to the time taken for air to pass through the storm.

Researchers have chosen storms for study which produced known severe weather and these storms have been consistently identified as supercells. However, the statistical importance of the relatively few supercells, as contributors to the total amount of recorded severe weather, has generally been lacking. Nelson (1976) has supplied some of the needed statistics, at least for Oklahoma hailstorms. He found that the average maximum hail size for the multicell hailstorm is 1.9 cm, while the average for the supercell is over 5.3 cm. The average maximum width of the hail swath for the multicell storm is 10 km and for the supercell is 20.2 km. Eight of the ten supercells in Nelson's study spawned severe weather other than hail, six of them producing funnel clouds or tornadoes. In contrast, other severe weather was noted in only four of 17 multicell storms and none produced tornadoes. Browning and Foote (1976) and Summers (1972) also conclude that while supercell storms constitute a small proportion of all hailstorms, they cause a disproportionate amount of damage owing to the large hail size, duration and extent of the hail, and other associated severe weather as well.

The discovery and documentation of the supercell storm occurred in the early 1960's (Browning and Ludlam, 1962; Browning and Donaldson, 1963; Browning, 1964, 1965a,b). The well-known supercell characteristics, as determined by Browning, are a sloping overhanging echo (most often) on the right flank, a vault which penetrates the overhang beneath the highest storm top, and a hook echo partly surrounding the vault in low levels.

The most widely accepted name for the region beneath the extensive mid-level overhang echo is the weak echo region (WER). The vault is now frequently called the bounded WER (BWER) (Chisholm, 1973; Browning and Foote, 1976). All of these features are illustrated in Fig. 1 through 3 and will be discussed in the following section.

The WER or BWER identifies the location of strong or intense updraft. Within the BWER, updraft is so strong that large precipitation particles do not have time to form in lower and mid levels and are prevented from falling back into the updraft core from above. There is a somewhat weaker but strong updraft producing the sustained echo overhang existing above a WER. Aircraft penetrations, radar tracked chaff, and balloon releases have verified the presence of such updraft in both the BWER and WER (Hart and Cooper, 1968; Marwitz and Berry, 1971; Marwitz, 1973). Maxima in updraft intensity, storm top height, echo intensity and reflectivity gradients exist when organized overhang is present (Marwitz, 1972b). Marwitz (1972c) observed that as updrafts within a WER weakened, the WER filled with echo and developed or collapsed downward.

Studies using high-resolution radars have found that a WER exists in most severe storms, whether multicell or supercell (e.g., Chisholm, 1973). It has also become evident that not all storms fitting the supercell definition contain a BWER, many simply have a WER. In the multicell severe storm the WER may be less persistent than in the supercell.

Many studies have emphasized the nearly steady or time-independent character of the WER and other radar depicted supercell characteristics. However, recent investigations show that the supercell most frequently undergoes a continuous evolution with periods of steadiness usually less than one hour (Burgess, 1974; Lemon et al., 1975; Lemon and Burgess, 1976; and Burgess and Lemon, 1976).

The first documented supercell occurred in Wokingham, England (Browning and Ludlam, 1962). Since then they have been observed in Canada (Chisholm and Renick, 1972), the Soviet Union (Sulakvelidze et al., 1967; Marwitz, 1971), and nearly all areas of the United States east of the Rocky Mountains. Thus, the supercell storm is not a regional entity, but a preferential organization resulting from an intense, moist, convective updraft and atmospheric physics governing such processes.

Based on this paper and those studies previously referenced, it seems that the supercell storm is responsible for the majority of severe thunderstorm damage. Further, it is quite likely that the vast majority of thunderstorms which produce significant tornadoes are of the supercell type. While the techniques and criteria presented here were primarily developed to detect the supercell storm, they work well in identifying the multicell storms which produce significant severe weather.

3. STORM UPDRAFT-ECHO RELATIONSHIP

The discussion in section 2 emphasized the strong or intense updraft. In general, it is updraft strength which determines storm severity. *Thus, for warning purposes, it is logical to look for updraft strength indicators.* Since, in general, a storm's echo top height and peak reflectivity can be related to updraft strength, these characteristics are currently used as indicators of storm severity.

To picture the relationship of the intense updraft to the resulting radar echo, a highly simplified, but quite useful analogy is proposed here. Imagine the updraft as a vertically pointing water fountain observed during a windy day. The water droplets of the fountain stream (being analogous to precipitation particles generated in the updraft) are carried away by the strong winds and fall to the ground some distance away from the fountain. The area where the water descends to the ground, downwind from the fountain, is analogous to the thunderstorm precipitation echo in low levels. Of course, in the environment of a severe thunderstorm, the wind typically veers and strengthens with height which is ignored in the analogy (as is updraft rotation). The point to be emphasized is that most of the radar echo over the lowest one-third of its depth represents precipitation generated within the updraft, but which has fallen from high levels after being carried downwind in environmental flow.

Keeping this analogy in mind, it is easier to understand the relationship of updraft strength to the vertical and horizontal echo distribution in thunderstorms (Fig. 1 through 3). The environmental flow in these schematics is that typical of severe thunderstorms. Speed shear exists with relatively strong winds aloft and the direction veering with height (southerly flow at the surface becomes westerly aloft). In this and following sections, the term "mid level" refers to a height range from about 5 km (16,400 ft) to 12 km (39,000 ft). Low levels refer to a height range from about 1.5 km (5,000 ft) downward.

A weak to moderate updraft is influenced to a large extent by the environmental winds. As the updraft air rises, it is forced downstream by the surrounding wind field. Precipitation particles forming in the updraft fall out as they form. The result is that the storm top, mid-level, and low-level reflectivity cores are generally aligned one below the other in a vertical fashion (Fig. 1a). Viewed on a PPI, there are no strong reflectivity gradients, no mid-level echo overhang (i.e., WER), and the mid-level storm core and echo top are found over the low-level core (Fig. 1b). In environments with quite strong mid- and high-level winds, the storm may even tilt downwind with height so that the storm top is downstream (relative to mid- and upper-level winds) from the low-level echo core. Storms having a structure as in Fig. 1, and reflectivities of 40 dBZ or greater, are usually found to be associated with heavy rain, and if any hail exists, it is small ($\leq$ 1.0 cm, .4 inch diameter).

If the updraft is stronger, as in Fig. 2a, it rises with less of a slope than the previous example and ascends to a greater height. The storm, when in this development stage, is considered severe but may be either a strong multicell or supercell storm. If the storm is multicellular, more than one echo top will exist. The storm top, or at least one of the tops in the multicell case, and mid- to high-level echo core are now above the strong low-level reflectivity gradient on the updraft storm flank (Fig. 2b). Note that the low-level echo core has also shifted toward the updraft flank, resulting in strong reflectivity gradients there. The mid-level echo overhang above the WER projects out beyond the edge of the low-level echo (or edge of the strongest reflectivity gradient) by about 6 to 25 km (3.2 to 13.5 nmi). The overall echo is usually moving more slowly and appreciably to the right of other nonsevere echoes. This echo configuration identifies a hailstorm and, when obtained with a WSR-57 radar, accompanies or precedes (by up to 30 min) the occurrence of large surface hail of 2.0 cm (3/4 inch) or greater. At this time, surface winds are strong and gusty, but generally less than 25 m s^{-1}, 50 kt (below severe proportions). The low-level echo in Fig. 2b is also characterized by strong or intense reflectivity gradients (defined here as values

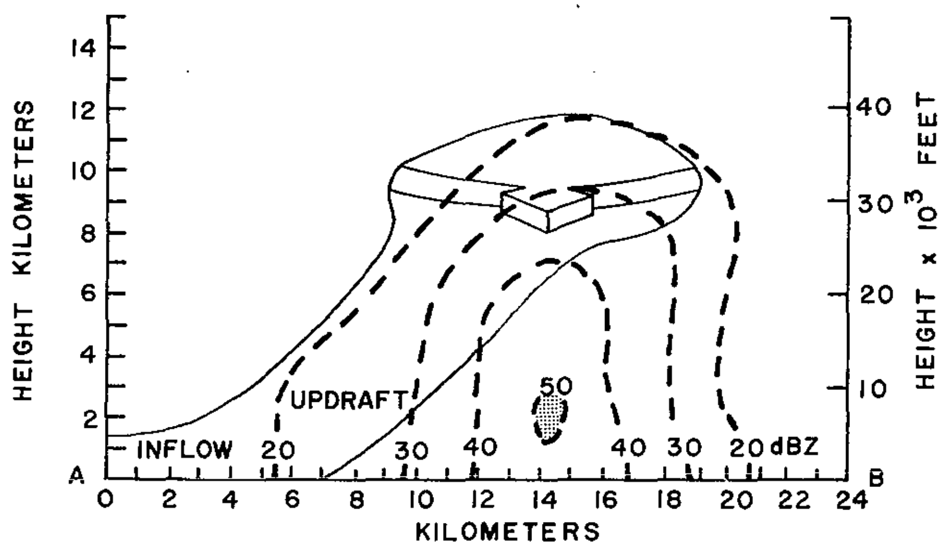


Figure 1a. Schematic diagram of a vertical cross-section or Range Height Indicator (RHI) radar display of a thunderstorm with the low-level inflow, a moderate updraft, and outflow aloft (solid lines) superimposed. Radar reflectivity (dashed lines) with reflectivities greater than 50 dBZ stippled.

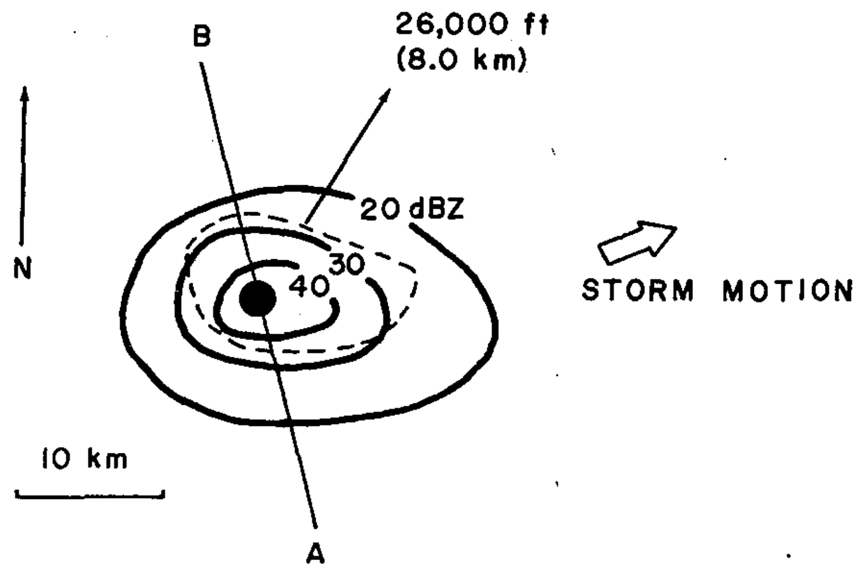


Figure 1b. Schematic composite of the same moderate thunderstorm as in Figure 1a, but as seen on a radar VIP PPI during a tilt sequence. Solid lines are the low-level reflectivity contours. Dashed line outlines the echo ≥ 20 dBZ derived from the mid-level elevation scan. The black dot is the location of the maximum echo top from the high-level scan.

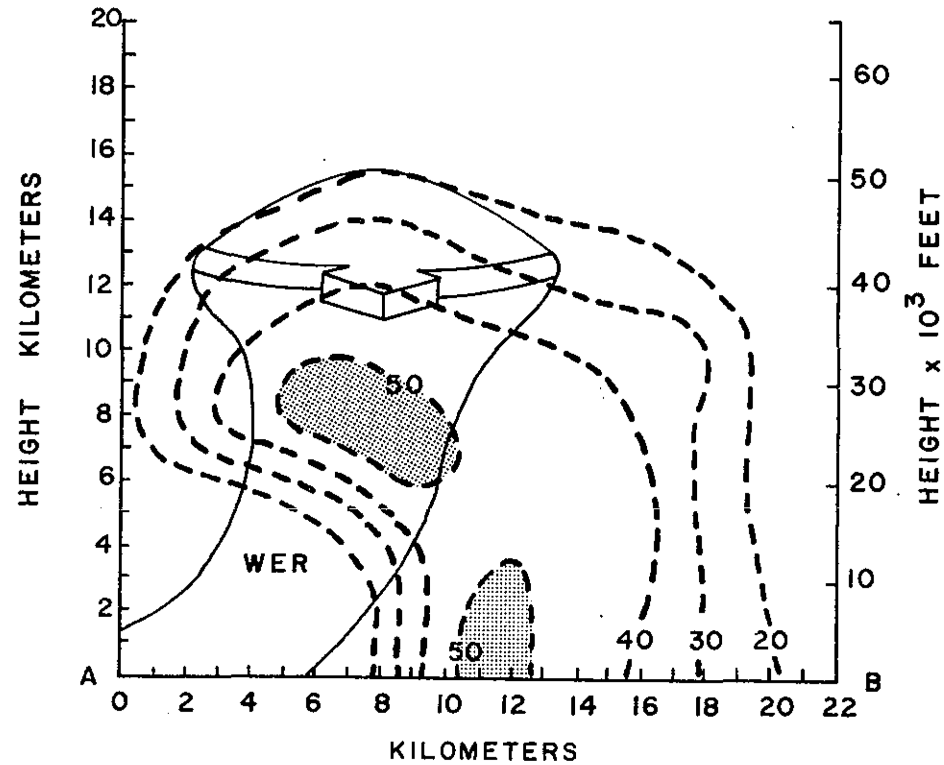


Figure 2a. Same as Figure 1a, except that the updraft is strong. The WER is the weak echo region.

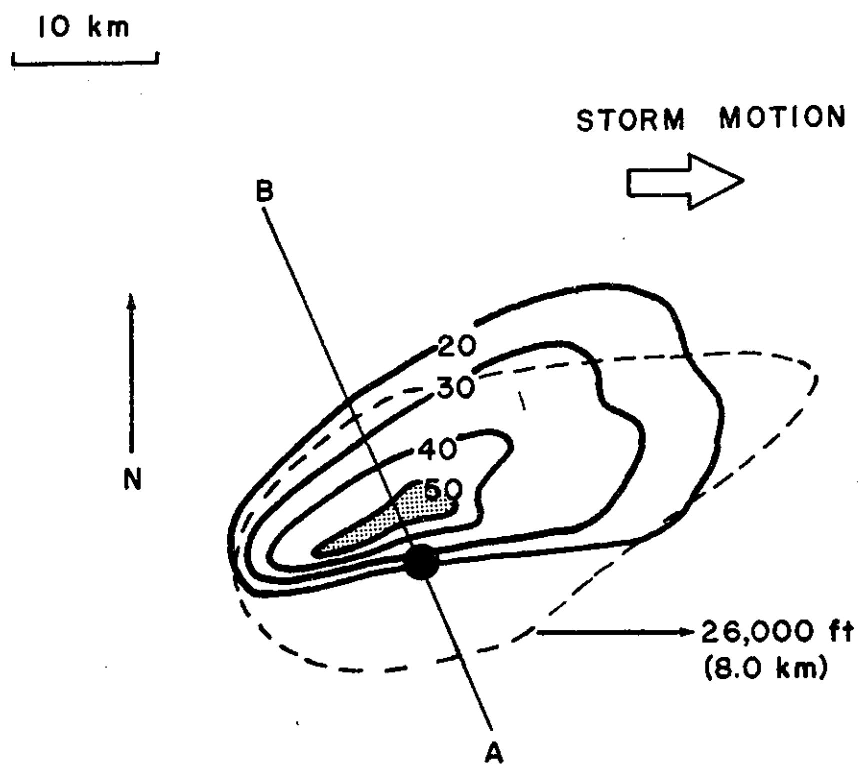


Figure 2b. Same as Figure 1b, except line AB corresponds to the cross-section in Figure 2a.

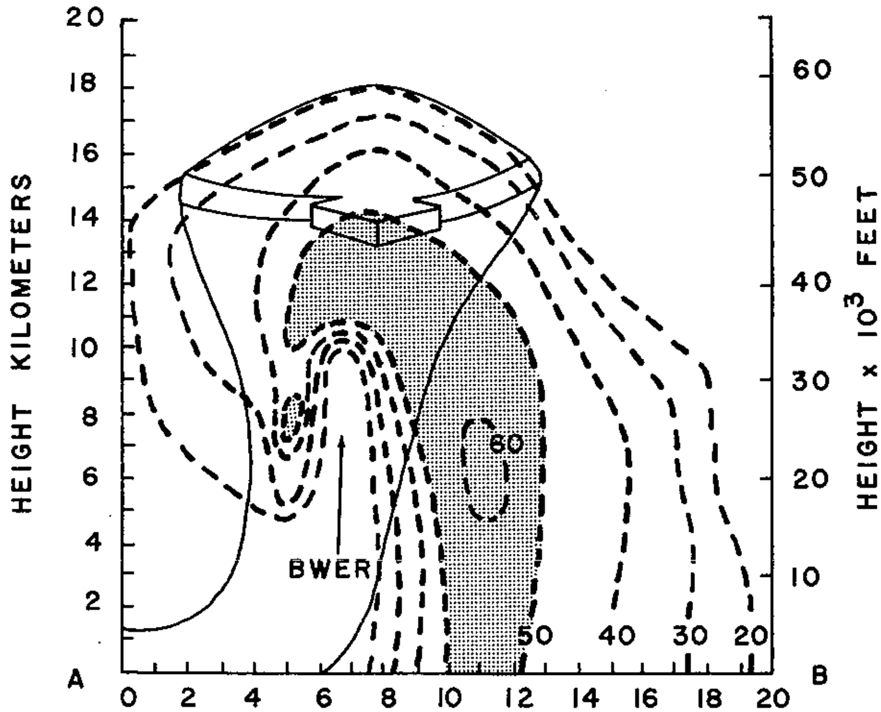


Figure 3a. Same as Figure 1a, except the updraft is intense.

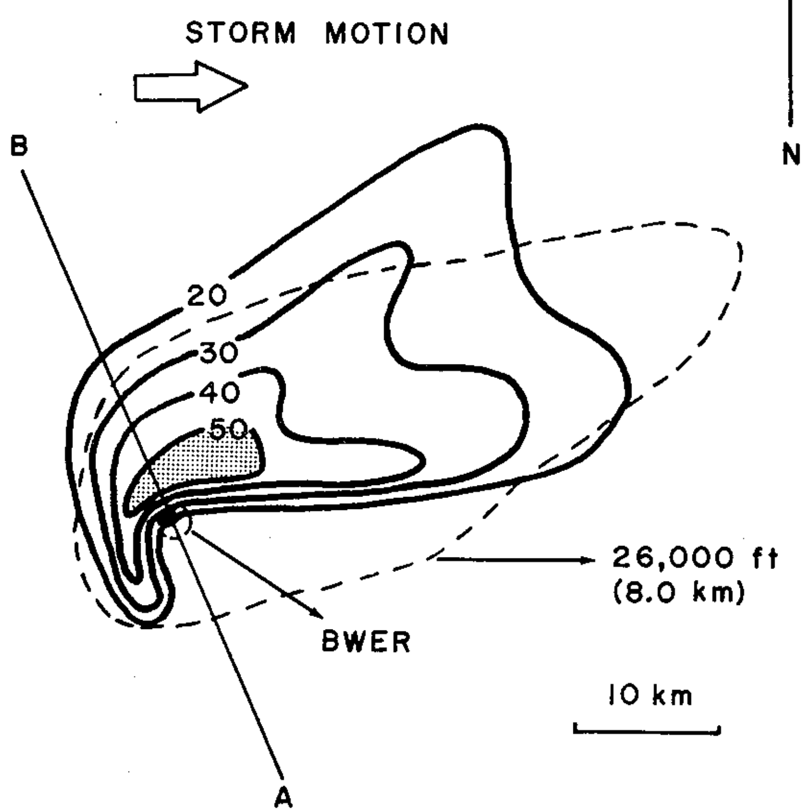


Figure 3b. Same as Figure 1b, except that the line AB is the cross-section axis of Figure 3a and the BWER is the location of the bounded weak echo region.

> 8 dBZ km^{-1}) usually associated with the strong updraft or at times downdraft (Nelson, 1977) on the storm flanks. Regions where much less or no updraft (or downdraft) exists have weaker gradients.

When a storm acquires an intense updraft and radar resolution is sufficient (storm most often must be within 110 km, 60 nmi), a detectable BWER may develop (Fig. 3). The updraft rises nearly vertically despite strong environmental winds and storm top may rise above 18 km (60,000 ft). The BWER is capped above by strong reflectivities and further aloft by the storm top. For all sufficiently documented Oklahoma cases examined to date, maximum surface hail size equaled or exceeded 4.5 cm (1-3/4 inches) (and has exceeded 11 cm, 4-1/4 inches) whenever a storm, detected by the WSR-57 radar having a 2° beam width, possessed a BWER. During the intense phase, surface winds often exceed 25 m s^{-1} (50 kt) and funnel clouds occur. In the rare cases of long-lived, quasi-steady storms, tornadoes may accompany this echo configuration.

Beneath the overhang (Fig. 3b), the low-level echo is usually characterized by a concavity bounded at the rear by a pendant or hook echo and bordered by intense reflectivity gradients. The storm top is usually located above the apex of, or over the concavity, but may also be over the pendant echo itself. (The pendant and hook echo are considered of equal importance and henceforth no distinction will be made, but will be referred to as "pendant" echoes only.) As in the storm with an unbounded WER, the low-level reflectivity core is shifted toward the updraft flank. A storm of this type is definitely a supercell. When a storm is in the supercell stage, a few peripheral cells which are much smaller may be contained within the large echo mass (Lemon, 1976a).

4. SUPERCELL STORM EVOLUTION

Storms with the characteristics discussed and exemplified in Fig. 1 through 3 can be alternately viewed as different stages in the development of one storm. In fact, a storm assuming the characteristics of the intense supercell phase (Fig. 3) will always pass through the hailstorm phase (Fig. 2) first. Details regarding that evolution are now considered.

While the quasi-steady state supercell has been emphasized in much of the published research, only two of the well-documented severe storms examined to date in this study were of that type. It is estimated that approximately 90% of the supercell storms evolve in a slow but continuous fashion and that severe weather production at the ground follows a consistent, predictable pattern directly related to radar echo evolution. The details of this relationship are dependent on radar resolution and are also still somewhat uncertain. More data are currently being gathered to clarify the relationships presented here.

Research has shown that the precursor to the supercell is frequently the nonsevere multicell storm (Browning and Ludlam, 1962; Browning and Atlas, 1965; Lemon, 1970; Nelson, 1977; Burgess et al., 1977). Each cell in the series developing on the updraft flank of the storm becomes stronger than the one previous, until one cell becomes large, dominant and is sustained for long periods. An alternate pattern of multicell to supercell development occurs as the time interval between successive cell development becomes so short that only one cell of the supercell structure results. During either of these sequences, the radar echo becomes larger and stronger and is most likely to become severe. This conclusion is borne out by Brandes (1972), who found that statistically the largest and most intense storms are the most severe. *However, unless the mid-level echo is strong ($\geq$ 45 dBZ) and the storm has a WER, then it is not likely to be severe despite its size.*

The first indication that an existing storm is becoming severe occurs when the mid-level echo increases rapidly in size and/or intensity as the WER develops. Concurrently, the maximum echo top shifts from over or downwind of the low-level core toward the updraft flank. The top appears over the strong reflectivity gradient or even outside the low-level echo above the developing WER. *It is important that both the shift in echo top and mid-level echo overhang development are present before the storm is interpreted as severe.*

In nonsevere multicell storms, new cells develop on the inflow flank and first become evident in mid levels producing short-lived echo overhang, but without shift in the maximum storm top. At other times, some shift in echo top may occur without overhang development. When both indications (the development and intensification of mid-level echo overhang and shift in echo top) occur concurrently or in close succession, the storm is severe, but there is sometimes little change in the surface echo for 5 to 15 min. It is not until the precipitation generated in mid levels descends that significant changes occur in the low-level echo.

When a substantial amount of mid-level echo overhang exists (~6-25 km) and the echo top has shifted, then a WER exists. Within 30 min of WER development, hail $\geq$ 2.0 cm (3/4 inch) begins to occur at the surface. Surface winds also begin to increase and the echo usually slows and turns from 15 to 100° to the right, while the low-level echo core shifts toward the updraft flank.

If the storm develops an intense updraft and radar resolution is sufficient, a BWER may form and be detected. Some tilt or slope of the BWER may occur from the surface to storm top, but continuity can be followed through the tilt sequence. When the BWER occurs, very large hail ($\geq$ 4.5 cm, 1-3/4 inches) is falling and strong winds are also being produced.

After the WER forms, and during the BWER formation (if it is detected), the right rear echo flank will often swing southward forming a pendant echo. Also, during the WER (or BWER) existence, the echo top reaches its greatest vertical extent. With time, the BWER ceiling (i.e., the strong vertical reflectivity gradient where the BWER becomes an echo core aloft) lowers, reflectivity within the BWER increases, and it becomes smaller. During the BWER collapse, the mid-level echo overhang will frequently decrease in area while the low-level echo increases. Echo top also begins to lower.

It is during the BWER existence and its collapse stage that the fall of largest hail takes place (Browning, 1965a; Burgess, 1974; Lemon et al., 1975). It is also during BWER collapse that the low-level pendant begins to "wrap up" (typically swings southward and eastward relative to the parent echo body), tornado production begins, and very strong damaging straight winds have their highest probability (Brown et al., 1973; Lemon et al., 1975).

As the collapse proceeds, the low-level pendant completes the wrap up and disappears, the low-level echo increases in size and may begin to weaken, and the echo top lowers, generally from 2 to 7 km (6,500 to 23,000 ft). It is also during this time that tornado probability is greatest and the tornado reaches its largest size. Precipitation has descended to low levels from mid levels surrounding the rotating updraft, resulting in a circulation center well within the low-level echo. The echo top is still near the circulation center, and thus has shifted back near the echo core. Echo overhang extent has lessened noticeably and hail sizes are rapidly lessening and amounts decreasing.

By the time of tornado dissipation, the echo has typically weakened somewhat and is often a part of a solid squall line with no remaining indications of strong updraft; i.e., no BWER, WER, and decreased reflectivity gradients. The echo top is over the echo core. The storm also often becomes multicellular once again.

New updrafts (especially if the echo remains separated from other echoes) may cycle through the above evolution with repeated severe weather and tornado production.

Present indications are that when surface dew points are marginal for severe weather ($\geq$ 10C, 50F), the expected hail sizes may not occur and the intensity of other severe events will be difficult to anticipate even with the above radar signatures (Williams, 1976). However even with marginal environmental conditions, the storms having the severe structure will likely produce severe weather to a limited extent.

5. OPERATIONAL APPLICATION

With the present knowledge of severe storm structure and its generality, radar warning techniques and warning criteria can be addressed from a meteorological (rather than the current empirical) approach using only the PPI VIP data display. Because of radar resolution and sampling restrictions, using an S or C band radar with a beam width of about 2° and pulse length of about 2 km or less, the techniques described here are effective at a range interval from ~ 40 to 200 km (22 to 110 nmi). With more narrow radar beam widths, the effective outer range limit can be extended.

5.1 The Tilt Sequence

A forecaster does not confine his data to the surface and perhaps one rawinsonde sounding, but instead looks at the horizontal distribution of meteorological variables at several atmospheric levels. Similarly, the weather radar specialist also needs to know the horizontal radar echo distributions at low, mid, and high levels for severe storm detection and warning.

This is not the same as taking one low-level PPI scan and several RHI observations. In fact, if the radar is not located properly, relative to the storm, the WER may not be detected using the RHI only. Therefore, VIP radar data should be acquired using a PPI tilt sequence lasting an average of 3 to 6 min and should be repeated an average of every 10 to 12 min.

The vertical step interval for the tilt sequence is a function of range to the echo as well as desired vertical echo resolution. A 2° interval is generally sufficient until approaching the storm top when 1° data are preferable for determining top height. The interval is variable, however, and can be selected or changed depending on the characteristics of each situation. A simple nomogram can be used effectively to convert antenna elevation angle to height (Fig. 4).

In order to conveniently compare the echo distributions at various heights, tracings are made on the PPI display face. During the tilt sequence, intermediate (mid-level) data should be traced first. This is done in order to determine the extent (if any) of echo overhang when the antenna returns to the lowest scan level (0 to .5° elevation). (When the storm is beyond about 100 km, 55 nmi, the lowest scan level should always be 0° elevation.) Since the maximum echo overhang can occur at heights from 5 to 12 km, it may be necessary to trace the echo at two or three intermediate elevation angles before that angle, at which the maximum occurs, can be determined. The height and, therefore, elevation angle at which the maximum overhang occurs can also vary from storm to storm. The elevation angle also changes with changing range of a storm for a fixed height.

As the PPI tilt sequence continues, a small dot is placed on the scope face marking the center of the echo at the highest elevation angle where echo is present. This dot represents the location of the maximum echo top. When the antenna returns to the lowest scan level, the mid-level and echo top tracings are then compared to the low-level echo as it appears on the PPI.

Care must be taken to minimize the time interval between the echo tracings aloft and the low-level comparison scan. If the storm is moving rapidly, an apparent overhang may appear; e.g., on the rear flank, because the low-level echo has moved significantly before the comparison with the mid-level echo and top position.

After an echo overhang has been identified, echo weak notches or holes may develop. These can be encircled on the PPI display scope and compared to echo top position and the low-level echo. If the echo weak hole is beneath

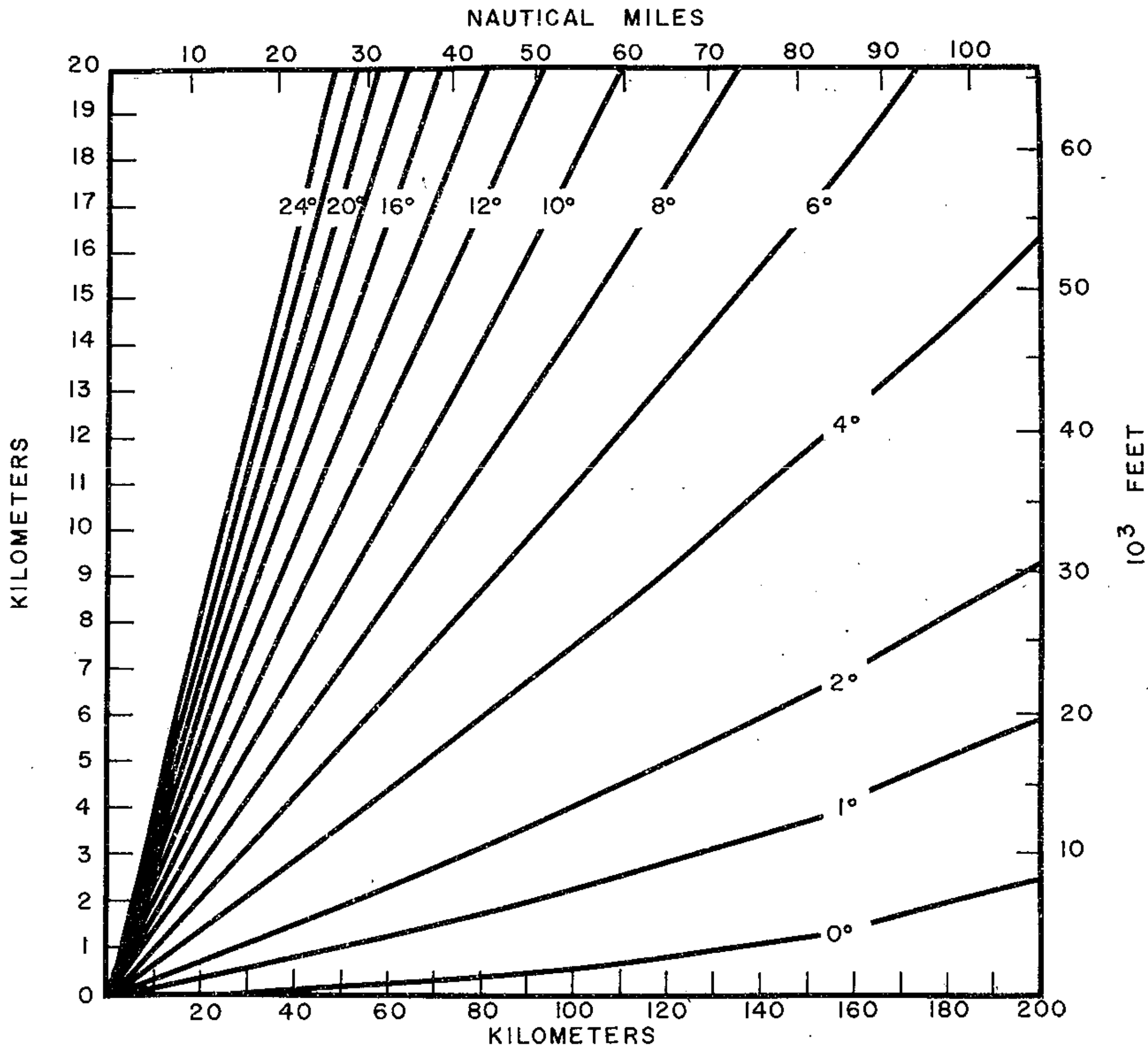


Figure 4. Height of the midpoint of the radar beam with the indicated elevation angle and range from the radar.

the echo top and over or near the edge of the low-level echo on the suspected updraft storm flank, the outlined area is probably a bonafide BWER.

5.2 Initial Scope Evaluation

A general outline is presented below for initial radar scope evaluation. From a given echo distribution on a PPI, those echoes having the greatest probability of developing intense updraft can be identified as found in this study and discussed by Hamilton (1969) and those references he cites. That is, those echoes which have the least competition for available low-level moisture are those most likely to be severe. These are typically:

1. The isolated echo (ahead of a thunderstorm line or otherwise).

2. Cells in a scattered thunderstorm line.

3. Cells in a broken line, especially those just north of a break in the line.

4. The echo at the south end of a thunderstorm line.

5. Cells at a bulge in a line; i.e., the cell which leads others.

5.3 Indicators of Severe Storm Presence or Imminent Development

Presented here is a summary of echo characteristics which generally occur in the first half of storm evolution. Most of these characteristics are illustrated in Fig. 2 and 3, and have been discussed in detail previously. Echoes having or developing intense updraft normally display several of the following characteristics <u>on the updraft storm flank</u>, i.e., generally the right rear, but occasionally rear or left rear.

1. At low levels, strong or intense reflectivity gradient with the echo core displaced toward that flank.

2. Low-level concavity bounded by strong reflectivity gradients.

3. Mid-level echo overhang extending appreciably (6 to 25 km, 3.2 to 13.5 nmi) beyond the low-level echo edge, capped above by a major reflectivity core ($\geq$ 45 dBZ) and further capped by highest echo top (usually found over the strong reflectivity gradient near echo edge). Beneath the overhang is the WER.

4. Within the echo overhang and extending vertically upward a circular region of low reflectivity typically $\leq$ 8 km (4.3 nmi) in diameter (BWER) may be present. This is located near the center or toward the south flank of the mid-level echo. The BWER is bounded by an intense reflectivity gradient, capped by the high-level echo core and by the echo top.

5.4 Other General Echo Characteristics

There are often other echo characteristics associated with severe storms; these are:

1. In the earliest stages of strong updraft development, mid-level echo strengthens and expands in areal coverage rapidly, becoming noticeably larger and more intense than other echoes which are not severe. This occurs as the WER develops and the maximum echo top shifts from over the core toward the inflow flank.

2. On the downwind storm flank (relative to mid- and high-level winds) the low-level echo may be characterized by two bands or lobes forming a V, occasionally the left lobe will exhibit anticyclonic curvature. This signature has been known as the "V notch." The cause is the deflection of flow on either side of the intense blocking updraft aloft carrying falling precipitation downstream along the resulting maximum wind bands. Blocking of environmental flow by intense updrafts in mid or upper levels is a well-established fact (Fujita and Grandoso, 1968; Brown and Crawford, 1972; Lemon, 1976b; Lemon et al., 1977).

3. During the transformation from a nonsevere to severe storm, the echo will occasionally split in a well-defined manner. Extensive documentation has been done by Burgess et al. (1976) and those references they cite. The split occurs in a manner resembling biological cell mitosis as two reflectivity cores form by separation of a single core along an axis perpendicular to storm motion. Separate WER's and echo tops develop in association with each core, one on the right storm flank, the other on the left. When the echo splits in this classical manner, the resulting storms deviate to the right and left of the mean winds. The right moving storm moves slowly and when it maintains the severe structure, it is associated with large hail, damaging straight winds and frequently tornadoes. The left moving storm moves much more rapidly and (when maintaining a WER which is found on the left or forward flank) is associated with large hail and high winds, but rarely tornadoes. (An example of a splitting storm is included in the Appendix.)

5.5 Additional Factors To Be Considered

It must be emphasized that a storm which has entered the typical supercell evolution can abort or cease severe weather production at any stage. Cessation is recognized by a premature collapse of the WER and echo top before BWER and/or pendant echo development. After pendant development takes place, cessation occurs with overhang collapse, but without pendant wrap up. If the storm aborts its evolution, then a cessation of severe weather results and warnings can be terminated.

Preliminary data show that a good indication of impending tornado development is the existence of a rather well-defined pendant accompanied by extensive overhang (WER). A tornado warning is deemed advisable, based on this study, when a BWER is detectable even if a pendant is not as obvious. Perhaps the best indication of tornado development is the wrap up of the low-level pendant echo. The collapse of storm top and BWER accompanying the wrap up are further confirmations. The use of these criteria for a tornado warning is questionable when dew points are marginal for severe weather. When environmental conditions are marginal, a well-defined pendant in low levels, in addition to the BWER, should exist before the tornado warning is issued.

A few comments concerning identification of a WER for determining storm severity are appropriate at this time. It should be observed that in upper levels echo overhang may result from precipitation carried downwind with anvil outflow. Beneath this region, low-level reflectivity gradients are commonly weak, unlike updraft areas. This overhang region on the downwind (relative to mid- and upper-level flow) storm flank should be interpreted as significant updraft only when accompanied by the maximum echo top above the overhang region or above an associated strong low-level reflectivity gradient.

Recent findings also indicate that a WER on the mid-level upwind echo periphery may be created by evaporation of falling precipitation in a developing downdraft (Nelson, 1977). While a WER of this nature does not have updraft and, therefore, an echo top associated with it, Nelson found that it was associated with a strong downdraft and rapid storm intensification to supercell proportions.

Mid-level echo overhang is not considered without a low-level echo. Echo overhang is present in the earliest stages of any thunderstorm development since first echo develops aloft. The overhang is important when it persists after the storm has a surface echo for approximately 20 to 25 min. At that point, if the echo top and low-level reflectivity gradient are favorable and the mid-level echo core is growing and is at least 45 dBZ, then a severe thunderstorm warning was found to be advisable.

It has been emphasized that the echo overhang must extend at least 6 km beyond the edge of the low-level echo and the mid-level echo core must be 45 dBZ. These are the minimum conditions. To avoid overwarning, when the storm first reaches these values, it is sometimes wise to wait 5 to 10 min to be sure that these are not transient characteristics, but will persist and increase. If the observed trend has been toward a rapid increase prior to reaching minimums, then the delay is probably not necessary.

In the past, merging cells have been emphasized as an indication of impending severe weather. Merger most frequently occurs as a result of adjacent development of storms or deviate motion of one cell. A storm strongly deviating to the right (as do most supercells) sometimes may merge with less intense nondeviating storms purely as a result of the right moving storm's motion. If the merger occurs such that the precipitation echo of the nondeviating storm is ingested or strongly interacts with the updraft of the supercell, that supercell will often weaken prematurely preventing or ceasing severe weather production.

The same merger process may occur on the forward or right forward flank, not interacting with the supercell updraft and will have little affect on the supercell intensity other than some increase in surface rainfall. If, on the other hand, the associated storm updrafts directly merge (as occurs very rarely), increased severe weather may result. Most severe weather associated with a storm is the result of that storm's character (Lemon <u>et al</u>., 1977) and not due to merger with other storms. Therefore, severe weather production during cell merger is usually coincidence and because of the rarity of updraft merger and hence storm intensification, merger of precipitation echoes should not be used for warning purposes.

5.6 An Illustrative Example

The following example (as well as others in the Appendix) provides an illustration for some of the techniques and storm radar echo signatures presented previously.

The 35 mm photographs of the PPI WSR-57 radar scope shown on the following pages were obtained from the National Severe Storms Laboratory (NSSL) located in Norman, Oklahoma. The data were collected using the integrated log contour (i.e., VIP) presentation with periodic or occasional tilt sequences, and used in a manner simulating real-time evaluation and warning issuance. The antenna tilt angle and time (CST) are included in the upper left-hand corner of each cropped photograph.

On 18 June 1973 in Oklahoma, very moist (21 to 25C, 70 to 75F dew points) unstable air existed in low levels and other environmental conditions were favorable for severe storm development. Although other storms were severe in central and southwestern Oklahoma (Doswell, 1977), only one storm is followed in this example - storm F. Storm E also developed the severe structure for a time. Although no verified severe weather was reported with storm E, news media included reports of 2.5 cm hail (1 inch) with the storm. The range marks are 40 km (21.6 nmi) and the integrator gate size is 1 km (.5 nmi). The integrated log contour film levels were set as follows:

Level		Intensity, dBZ
1	Gray	21-30
2	White	31-38
3	Black	39-45
4	Gray	46-54
5	White	$\geq$ 55

The position of the maximum echo top, relative to the low-level echo, is shown periodically or when needed, and is indicated by a small + (either white or black, depending on the background). When mid-level overhang data are indicated at 0°, the outline of the overhang is presented on the photographs by white dotted lines.

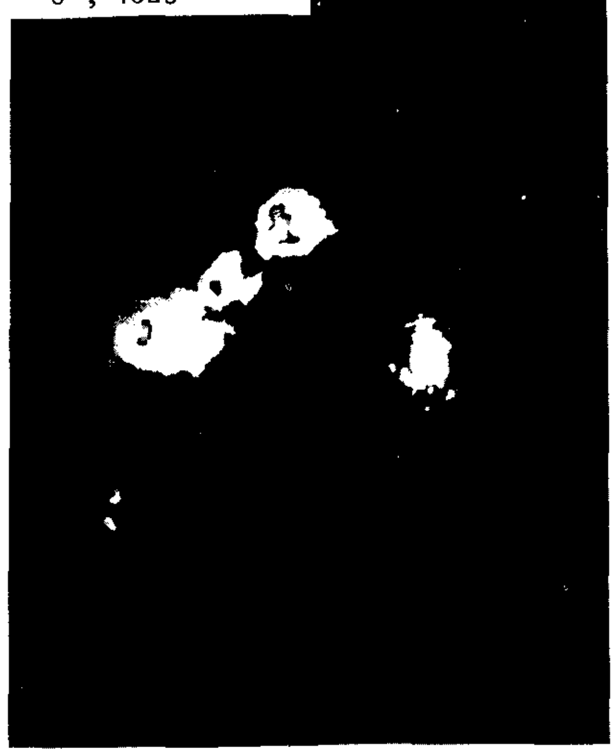
An initial evaluation of the radar PPI display at 1522 and 0° antenna elevation reveals a scattered to broken line of echoes. Just north of a break in the line is the largest strongest storm in existence. Storm F is in a favorable position for further development since there are no storms nearby to the south to compete with F for the low-level southeasterly flow.

0°, 1522

6°, 1524

0°, 1525

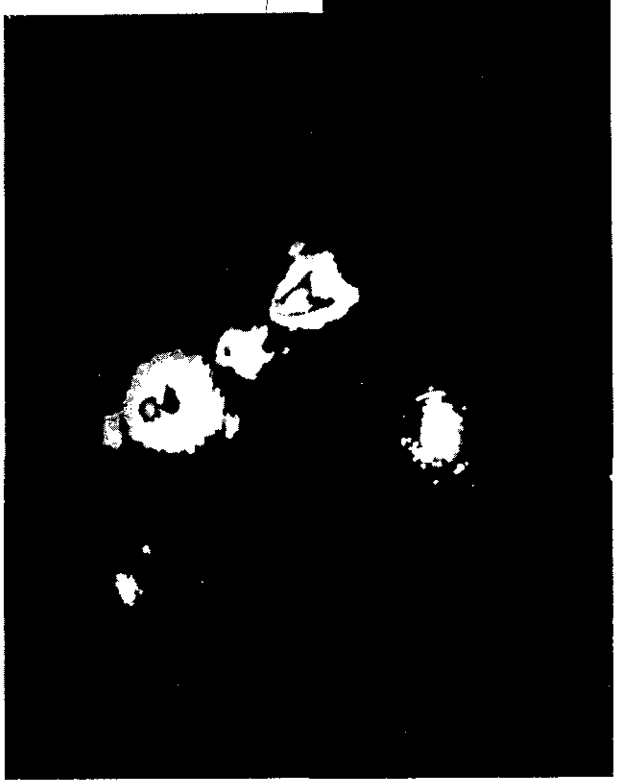
6°, 1526



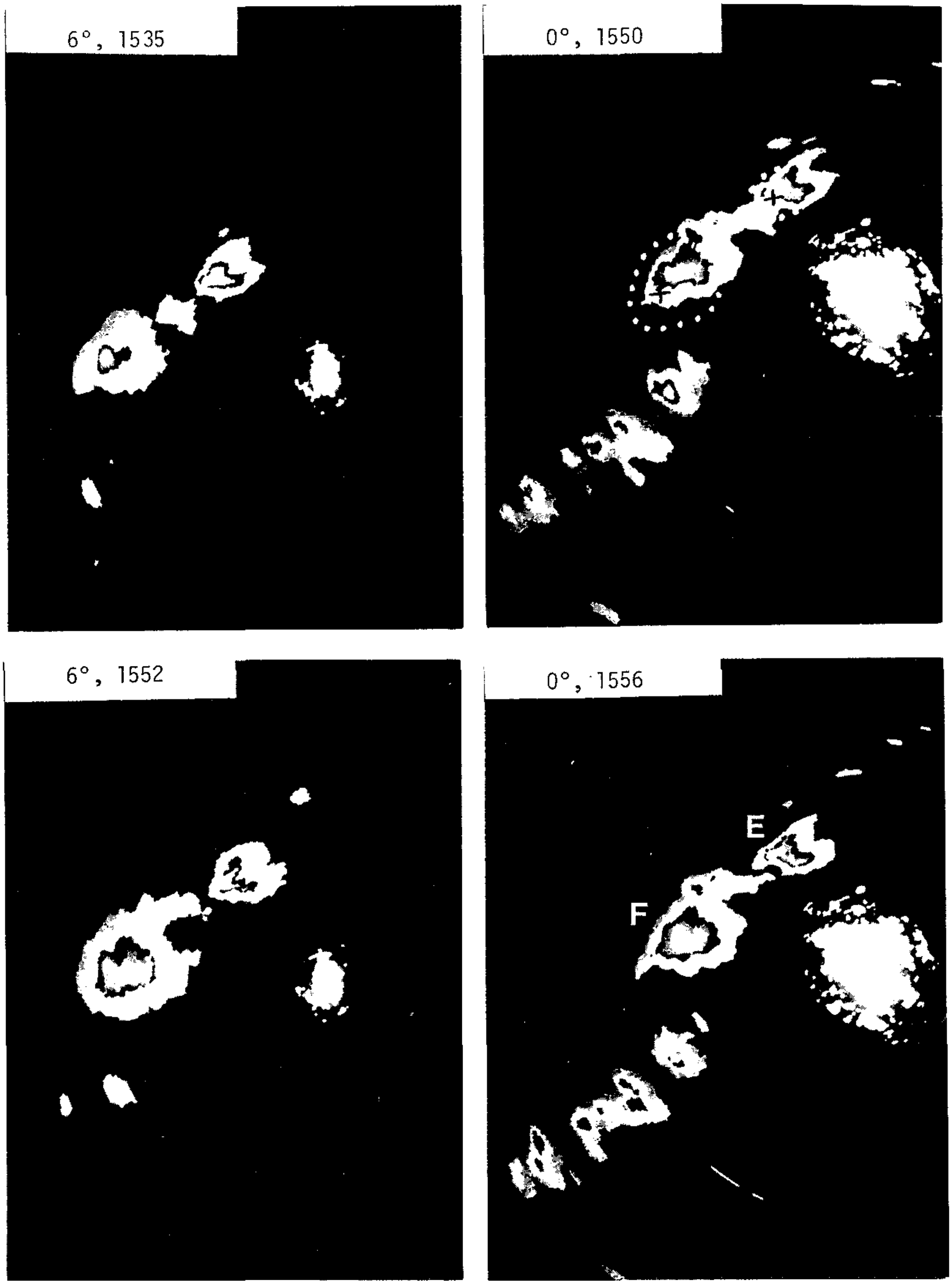
6°, 1529

0°, 1531

6°, 1532

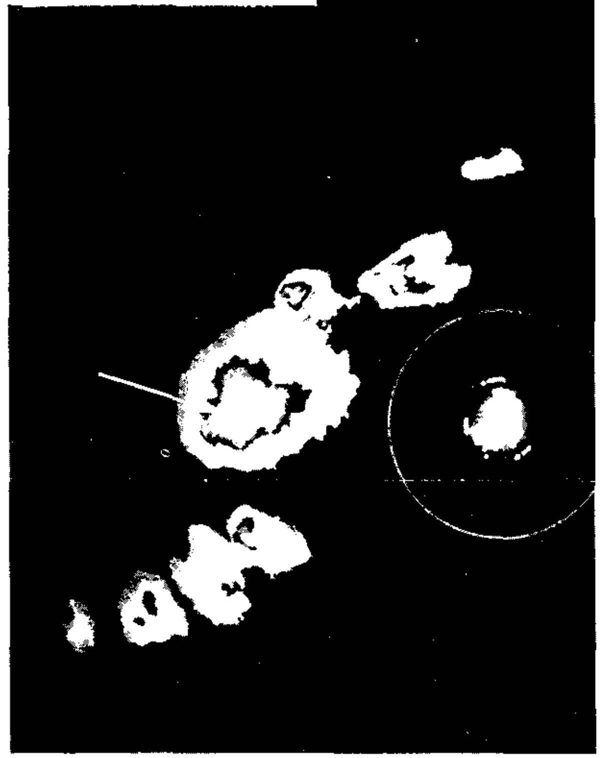


0°, 1533


6°, 1535
0°, 1550
6°, 1552
0°, 1556
E
F

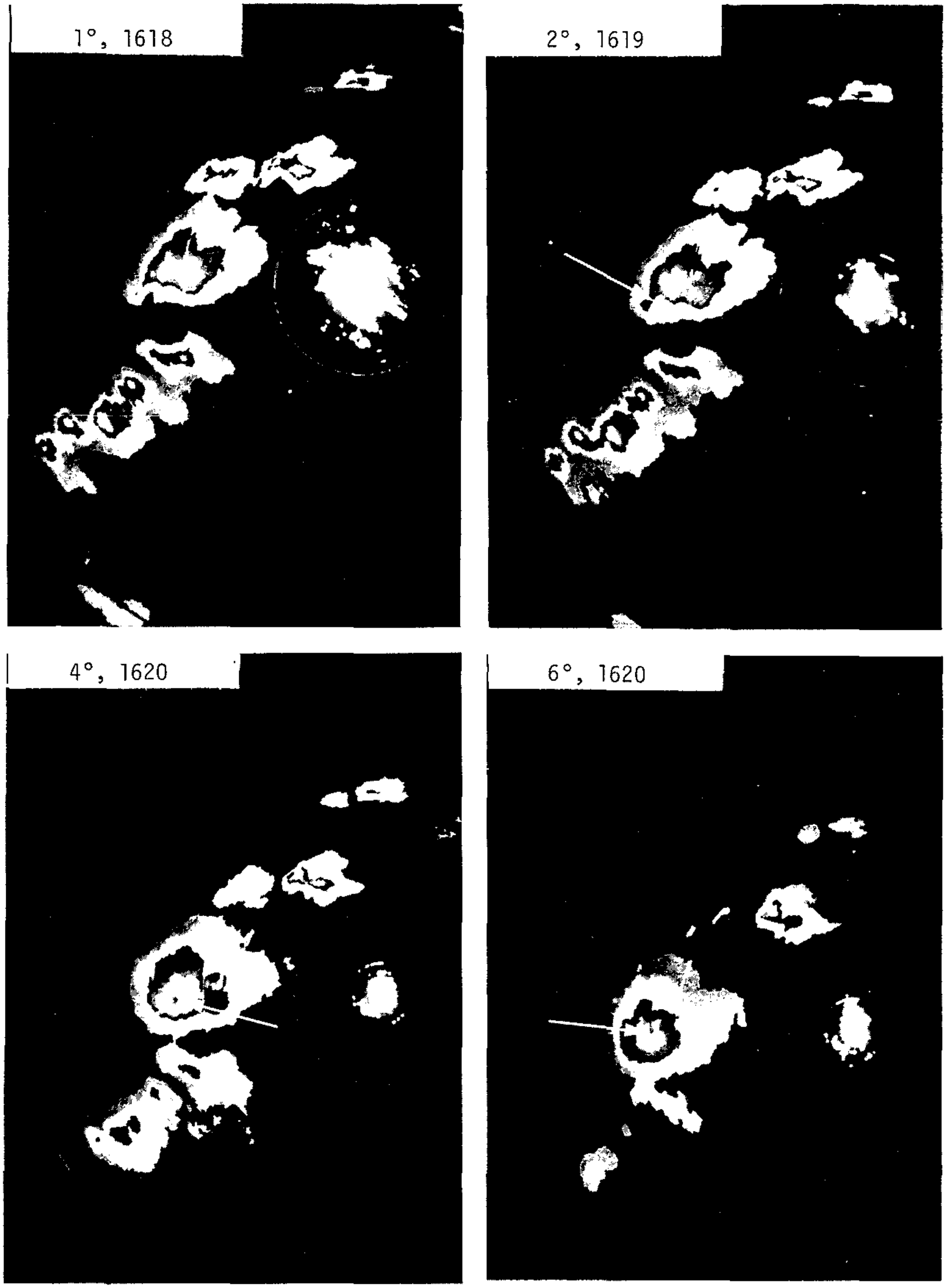
0°, 1605

4°, 1606

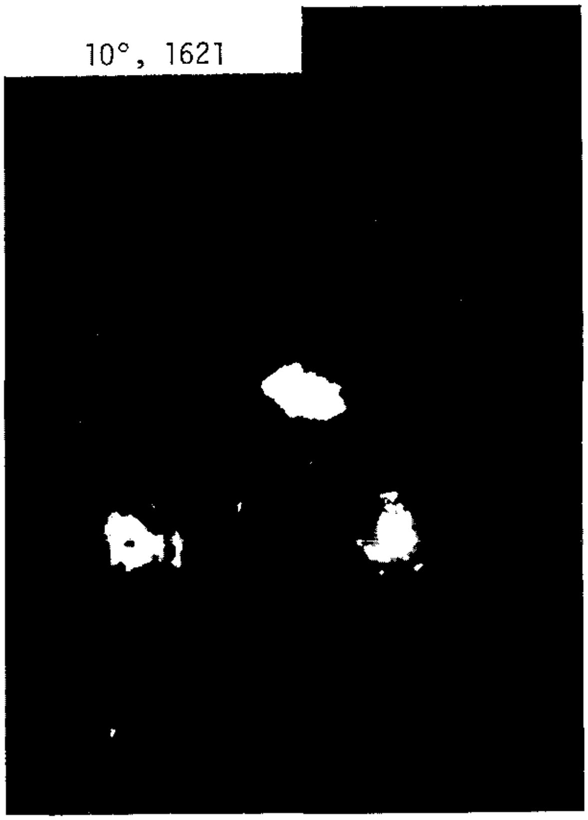


0°, 1609

0°, 1618


1°, 1618
2°, 1619
4°, 1620
6°, 1620

10°, 1621

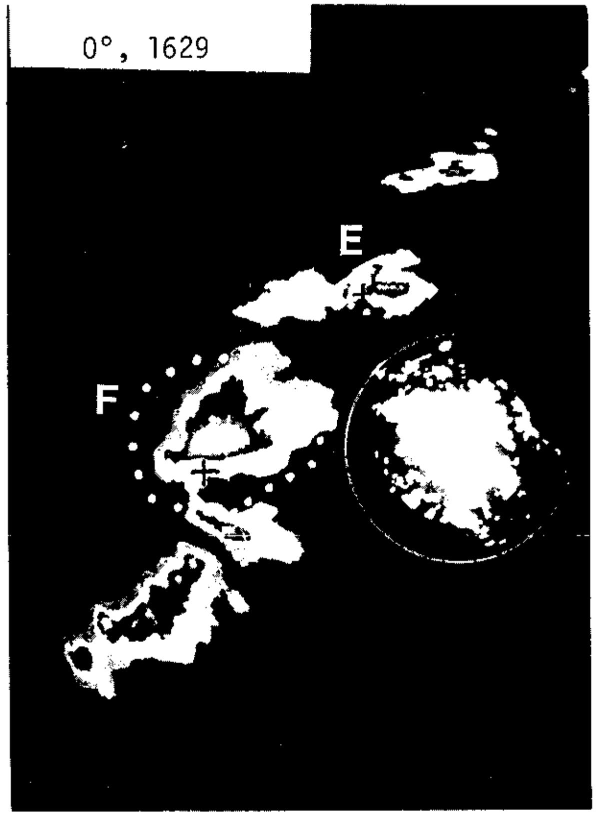


0°, 1622

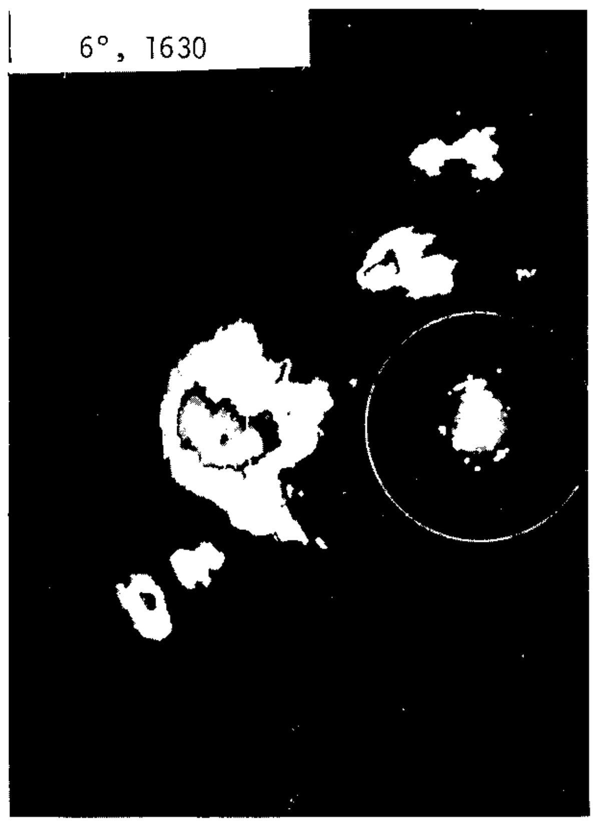
4°, 1623

0°, 1625


4°, 1626


0°, 1629
E
F


4°, 1630

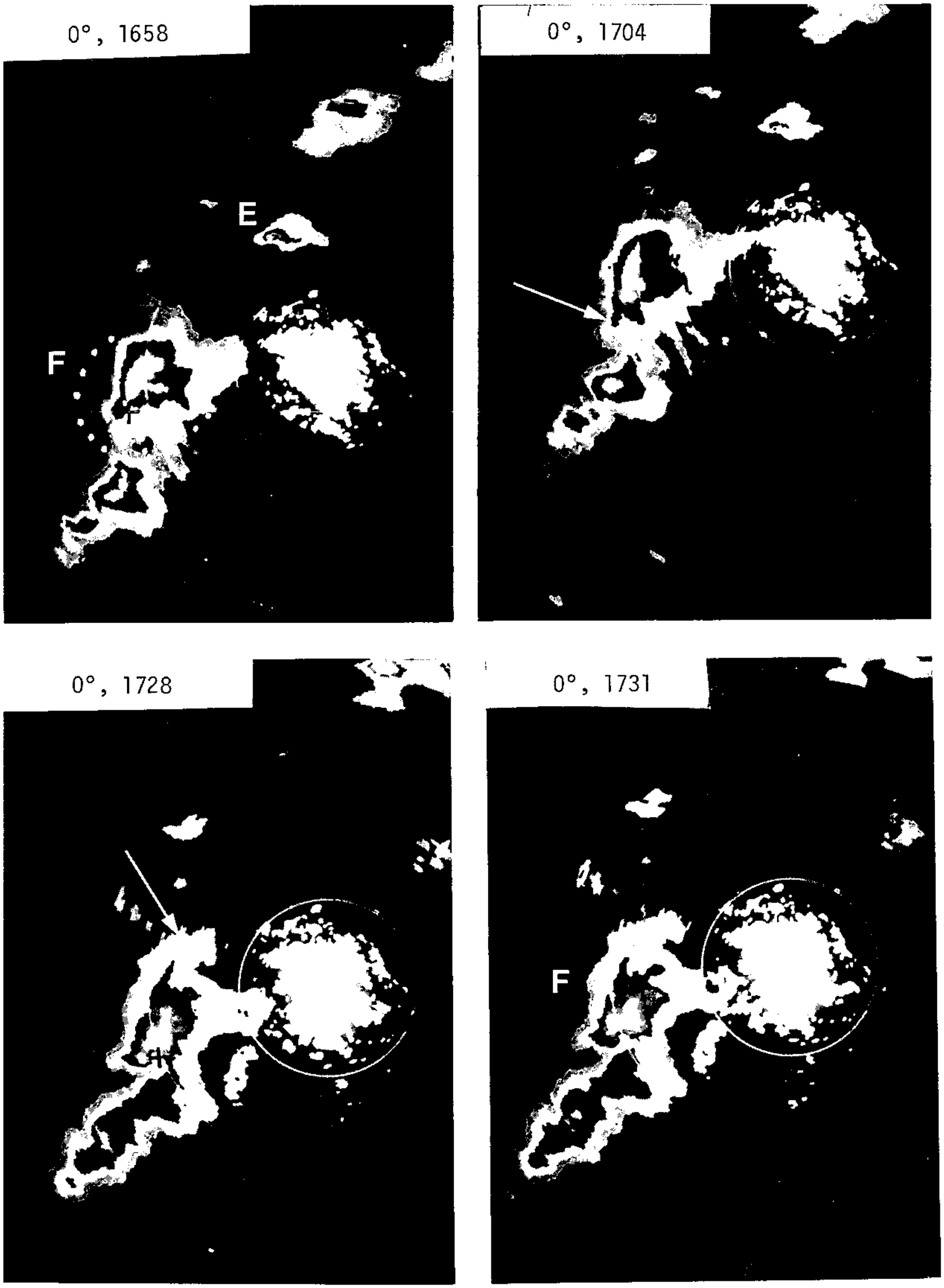

6°, 1630

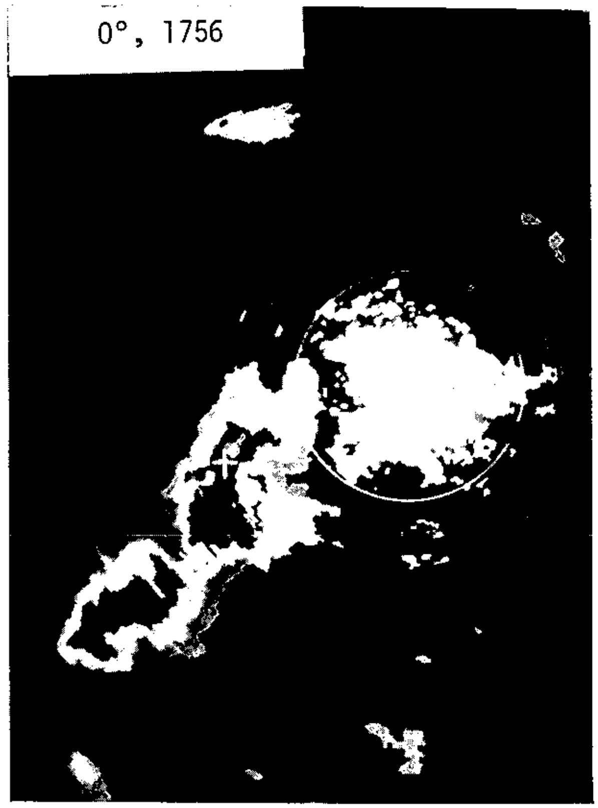

0°, 1641


6°, 1643


0°, 1645


6°, 1646


0°, 1658
E
F
0°, 1704
0°, 1728
0°, 1731
F



0°, 1522 - F - The storm has been moving from 236° at 11 m s^{-1} (21 kt). An extensive (about 9 km, 5 nmi) overhang as well as the shift in echo top was noted during the previous tilt sequence.

6°, 1524 - Although not the strongest, storm F is associated with the largest mid-level (at that range 9.9 km, 32,000 ft) echo.

0°, 1525 - The storm met the severe criteria as observed during the tilt sequence except for mid-level echo intensity which is reached in about 1 min.

6°, 1526 - Note the small fifth level core. In 2 min the mid-level echo has increased two VIP levels or at least 15 dBZ. Based on observed storm structure (mid-level echo overhang extent, intensity and top location), a severe thunderstorm warning is issued (valid 1526-1625).

6°, 1529 - The areal coverage of fourth level echo continues to increase although the fifth level core has dissipated.

0°, 1531 - Storm size has increased slightly, but the fifth level core has decreased steadily. The storm has turned sharply right, moving from 350° at 5.5 m s^{-1} (11 kt) or about 100° right of the mean wind.

6°, 1532 - A small fifth level core has redeveloped.

0°, 1533 - The fifth level core at 0° has dissipated entirely although the overhang has increased to 12 km (6 nmi).

6°, 1535 - An explosive intensification and growth has begun to occur in mid levels despite the weakening trend in low levels.

0°, 1550 - The rapid increase in storm size and strength is now occurring in low levels nearly 25 min after developing storm severity was evident in mid levels. (5 cm, 2-inch, hail was reported at this time.)

6°, 1552 - The area covered by echo greater than level three has more than doubled in 17 min. Total echo diameter for this supercell storm is about 56 km (30 nmi).

0°, 1556 - Echo growth has continued and beneath the overhang a possible pendant echo has developed. A tornado warning should be strongly considered now, but the decision was made to wait to be sure that this structure was persistent.

0°, 1605 - The pendant echo has persisted, overlayed above by the echo overhang (as it must to be bonafide) with the echo top in the proper region. The severe thunderstorm warning is replaced by a tornado warning (valid 1605-1705).

4°, 1606 - A developing BWER (arrow) is present which reaffirms the tornado warning decision.

0°, 1609 - Little change. (However, 11 cm, 4-1/4-inch, hail, damaging east winds, and three funnel clouds were occurring in the area of the strongest reflectivity gradient just south of the storm core.

0°, 1618 - 1°, 1618 - 2°, 1619 - 4°, 1620 - 6°, 1620 - 10°, 1621 - On the 0°, 1618 frame the maximum echo top position relative to the low-level echo is indicated. Note the BWER in the 2°, 1619 frame (arrow) through 6°, 1620. The mid-beam average height of each scan follows: 0°, 400 m (1,300 ft); 1°, 1,800 m (5,900 ft); 2°, 3,200 m (10,500 ft); 4°, 6,000 m (22,300 ft); 6°, 10,000 m (32,800 ft); 10°, 17,000 m (55,800 ft).

0°, 1622 - 4°, 1623 - 0°, 1625 - Only minor changes have occurred. The BWER is better developed and more obvious at 4°. Little change in structure has taken place.

4°, 1626 - The two fifth level core segments surrounding the BWER appear to be influenced by the mesocyclone circulation.

0°, 1629 - 4°, 1630 - 6°, 1630 - The BWER is filling with higher reflectivity echo as compared to the previous tilt sequence, and the top of the BWER is descending; i.e., BWER collapse is taking place. Note the echo to the south of storm F which is moving northeast and has begun to merge with the strongly rightward deviating storm F.

0°, 1641 - The small pendant echo in levels two and three extends due south from the southwestern echo flank. After the echo top reached a peak of 19 km (62,300 ft) at 1634, it has been subsiding since and is now 17.9 km (58,700 ft), see Fig. 5 for echo top changes relative to tornado production. Note that the merger of the smaller echo is nearly complete.

6°, 1643 - The small unbounded wedge-shaped indentation in the third level contour (arrow) is all that remains of the collapsed BWER.

0°, 1645 - (An intense tornado which lasts until 1657 has touched down near the tip of the third level contour (arrow in photograph) southwest of the storm top location.) Tornado production results from the intense rotating updraft (mesocyclone) which accompanies this storm and is unrelated to the merger process which occurred 18 km (10 nmi) east.

6°, 1646 - No trace of the BWER remains, only the large intense echo.

0°, 1658 - (The first tornado has just dissipated.) A second small echo has merged with storm F. Just west of the echo top is a poorly defined pendant echo in the third and fourth levels which swings east wrapping up by 1704.

0°, 1704 - (The second strong tornado is underway (arrow) from 1701 to 1712, again just southwest of the maximum echo top location.) The previous tilt sequence (1648-1651) revealed the extensive overhang persisting with the small pendant noted at 0°, 1658 and, therefore, the tornado warning expiring at 1705 is reissued 1705-1805 because the small pendant has just wrapped up, the severe structure persists and BWER collapse has occurred a short time before.

0°, 1728 - The echo top is shown, but not the overhang echo. A notch or indentation has developed beneath and just southwest of the echo top location. (A third tornado is on the ground beneath the broad ill-defined pendant echo in levels three and above, bounding the notch to the west.) The curved band of projecting echo on the north flank of the storm (arrow) has been explained by flow around a blocking rotating updraft in mid levels and found to occur with quite severe thunderstorms (Lemon, 1976b).

0°, 1731 - Little change in the echo structure has occurred. (The tornado remained on the ground until 1734.) The echo top has been decreasing and is now 15.2 km (50,000 ft) (see Fig. 5). Note the thunderstorm just south of, and beginning to merge with, storm F.

1°, 1732 - A rather well-defined hook echo in the fifth level core is located just west of the echo top position (not shown) and is wrapping up.

0°, 1756 - Storm F has weakened considerably as the echo to the south has merged with the updraft region of F cutting off low-level moist inflow. Overhang has dissipated, the echo top is very near the core, and the warning is allowed to expire at 1805. No further severe weather accompanied storm F.

Echo top fluctuations relative to storm evolution and severe weather production are illustrated in Fig. 5. Tornado production occurs in both the 18 June 1973 and 19 April 1972 cases (see Appendix) during echo top decline. This has also been shown in several recent studies (e.g., Lemon et al., 1975; Lemon and Burgess, 1976; Lemon, 1976c; and the papers they reference).

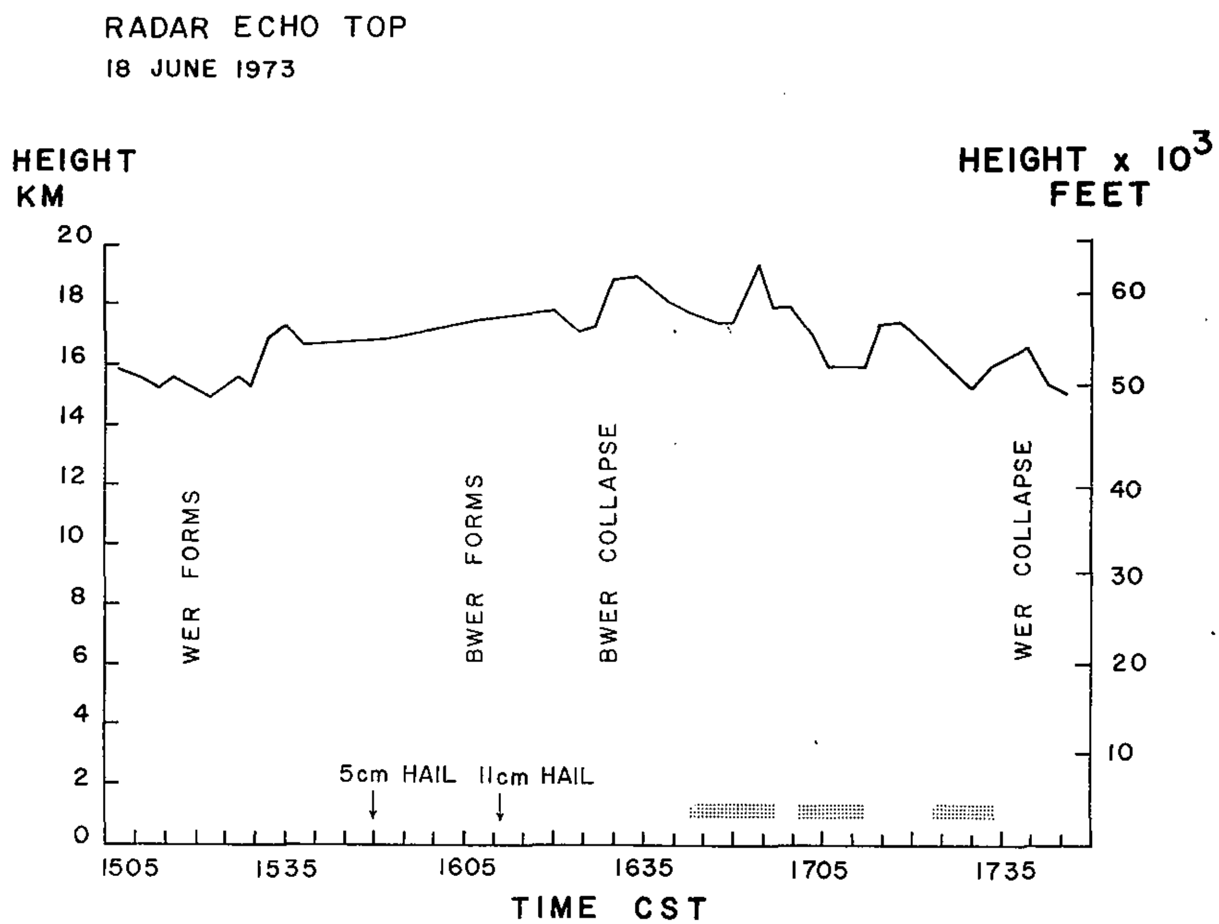


Figure 5. Graph of storm F echo top as a function of time. Tornado duration on ground is indicated by the stippled bars. Other echo and surface weather is included as indicated.

6. VERIFICATION OF THE TECHNIQUES AND CRITERIA

In order to evaluate these new radar techniques and criteria for severe thunderstorm and tornado prediction, detection, and warning, an evaluation tool called the critical success index (CSI) developed by Donaldson et al. (1975a,b) was used. The CSI takes account of both the false alarm rate (FAR) and the probability of detection (POD). The CSI, FAR, and POD range from 0 to 1.0. A perfect technique has a CSI of 1.0 corresponding to no false alarms (FAR=0), and 100% probability of detection (POD=1.0).

A relatively small data set of about 80 thunderstorms, 30 of which were confirmed severe, has been used to determine a preliminary CSI for the new techniques and criteria. The data were taken from 13 days during a 10-year period in Oklahoma. These days were chosen because significant severe storms were known to have occurred. The radar films for these days were used in a manner simulating real-time data acquisition, and warnings were issued and terminated using only criteria presented in this report and only VIP tilt sequence WSR-57 radar data. Verification was accomplished using Storm Data and ground and aerial surveys accomplished by NSSL personnel. The resulting CSI for both severe thunderstorm and tornado warnings combined was .71, with a POD of .93, and a FAR rate of .24. Foster (1976) used National Weather Service (NWS) manually digitized radar data to evaluate the current radar identification techniques. An average of his results indicates the current NWS CSI is approximately .13 with a POD of .47 and a FAR rate of .85. More specifically, Foster's results indicate that the averages for Oklahoma City NWS, in whose area the storms used as examples occurred, were CSI=.24, POD=.56, and FAR=.71. It is anticipated that if the new techniques were implemented operationally, its CSI would drop from the very high values mentioned above, but would still be significantly better than that of the current criteria.

In addition, the new techniques and criteria produced an average warning lead time before the first severe report of about 27 min. Several instances of lead times from 50 to 70 min were also obtained. Lead times of these magnitudes indicate that radar can actually have a very short-range predictive value.

7. SUMMARY

The present severe thunderstorm and tornado radar warning criteria, representing an almost entirely empirical approach to identifying a previously poorly understood phenomena, are in need of updating (Donaldson et al., 1975a; Foster, 1976). While presently we are a long way from completely understanding severe convection, our understanding has reached the point where a meteorological approach to radar warning criteria is possible.

The tornado and severe weather associated storm (whether multicell or supercell) produce a recognizable radar echo structural organization resulting from an intense moist updraft. These storms follow a consistent, predictable evolution directly related to the evolution of severe weather production. The use of the radar VIP in a PPI tilt sequence mode allows this knowledge to be translated directly into severe weather warning techniques.

In summary, the three derived criteria which must all be satisfied for a severe thunderstorm warning are:

1. Mid-level (5 to 12 km, 16,000 to 39,000 ft) echo greater than or equal to 45 dBZ exists.

2. Mid-level echo overhang extends at least 6 km (3.2 nmi) beyond the outer edge of the low-level (surface to 1.5 km, 5,000 ft) echo or beyond the strongest reflectivity gradient.

3. The highest echo top, which is above the low-level reflectivity gradient between the echo core and echo edge or outside the low-level echo, is on the storm flank that possesses the overhang.

A tornado warning requires that all the above severe thunderstorm criteria are met <u>and</u> either:

1. A low-level pendant (oriented generally at right angles to storm motion) exists in reflectivity contours of 20 dBZ and/or greater. (The pendant must be beneath or bounding the overhang echo on the west.) Or,

2. A BWER is detected.

When surface dew points are marginal for severe weather, the presence of a BWER is not sufficient, the storm must also be accompanied by a low-level pendant echo.

Those storms which attain only the severe multicell stage, i.e., do not develop the supercell organization, satisfy the severe thunderstorm warning criteria only. The multicell nature is identified by the presence of two or more echo tops with at least one top satisfying severe thunderstorm criterion 3.

While these techniques should improve our warning ability and timeliness, a number of severe thunderstorms produce severe events for which no recognized method of radar identification is yet possible. Only public and other reports can be used in detection and warning of the storms producing those events.

The techniques and echo signatures presented here can be used with any surveillance weather radar, but were designed using the WSR-57 radar. Specific hail sizes and expected surface severe weather are also presented and correlated with echo structures, but these relationships were again drawn using the WSR-57 radar. Any radar with a beam width of about 2° and integrator gate size of 1 to 2 km can, therefore, adopt the techniques and evolution presented here with confidence. Radars having smaller beam widths will more readily identify the echo signatures. Because of the increased resolution there may be some degradation in correlation of surface severe weather with echo evolution stages. However, until data become available for examination from these higher resolution radars, the general techniques and principles discussed here should be considered applicable.

Current plans are to continue to evaluate and refine the techniques presented here. It is also anticipated that if Doppler radar is adopted in the NWS as a warning tool, a combination of the techniques presented here and the Doppler velocity data would be most beneficial. This would especially be true for at least two reasons. First, the present indications are that the severe multicell storm is not characterized by a Doppler detectable mesocyclone vortex signature (Lemon et al., 1977). Second, there is sometimes difficulty in establishing mesocyclone existence with velocity data alone. In those cases, evaluation of that signature could be aided when considering the backdrop of storm reflectivity structure. It is also likely that not all radars would be equipped with Doppler capability; thus, those remaining conventional radar systems could use the techniques described here.

8. ACKNOWLEDGMENTS

The author is indebted to: the National Severe Storms Laboratory for providing much of the data for this study, Drs. Joseph T. Schaefer and Charles A. Doswell III of the Techniques Development Unit, Mr. Rodger Brown of NSSL, and H. M. Mogil, Meteorological Services Division, and D. W. Holmes, Sounding Systems Branch, both of the National Weather Service, for their critical review of the manuscript, and Deborah Barbieri for her patience and expertise in manuscript and figure preparation.

9. REFERENCES

Brandes, E. A., 1972: The use of digital radar data in severe storm detection and prediction. Preprints, 15th Radar Meteor. Conf., Boston, Amer. Meteor. Soc., 45-48.

Brown, R. A., and K. C. Crawford, 1972: Doppler radar evidence of severe storm high-reflectivity cores acting as obstacles to airflow. Preprints, 15th Radar Meteor. Conf., Boston, Amer. Meteor. Soc., 16-21.

__________, D. W. Burgess, and K. C. Crawford, 1973: Twin tornado cyclones within a severe thunderstorm: Single Doppler radar observations. Weatherwise, 26, 63-69.

Browning, K. A., 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. J. Atmos. Sci., 4, 634-639.

__________, 1965a: A family outbreak of severe local storms - A comprehensive study of the storms in Oklahoma on 26 May 1963. Part I. Air Force Cambridge Research Lab, Special Report No. 32, 346 pp.

__________, 1965b: Some inferences about the updraft within a severe local storm. J. Atmos. Sci., 22, 669-677.

__________, and D. Atlas, 1965: The initial development of a severe storm as observed by radar. Chapter 11, A family outbreak of severe local storms - A comprehensive study of storms in Oklahoma on 26 May 1963. Part I. K. A. Browning, Ed. Air Force Cambridge Research Lab, Special Report No. 32, 197-236.

__________, and R. J. Donaldson, Jr., 1963: Airflow and structure of a tornadic storm. J. Atmos. Sci., 20, 533-545.

__________, and G. B. Foote, 1976: Airflow and hail growth in supercell storms and some implications for hail suppression. Quart. J. Roy. Meteor. Soc., 102, 499-534.

__________, and F. H. Ludlam, 1962: Airflow in convective storms. Quart. J. Roy. Meteor. Soc., 88, 117-135.

Burgess, D. W., 1974: Study of a right-moving thunderstorm utilizing new single Doppler radar evidence. Master's Thesis. Dept. of Meteorology, Univ. of Oklahoma, 77 pp.

__________, and R. A. Brown, 1973: The structure of a severe right moving thunderstorm: New single Doppler radar evidence. Preprints, 8th Conf. on Severe Local Storms, Boston, Amer. Meteor. Soc., 99-106.

__________, and L. R. Lemon, 1976: Union City storm history. Chapter 5, The Union City, Oklahoma tornado of 24 May 1973. R. A. Brown, Ed. NOAA Tech. Memo. ERL NSSL-80, Norman, National Severe Storms Lab, 35-51.

__________, R. A. Brown, L. R. Lemon, and C. R. Safford, 1977: Evolution of a tornadic thunderstorm. Preprints, 10th Conf. on Severe Local Storms, Boston, Amer. Meteor. Soc.

Byers, H. R., and R. R. Braham, 1949: The Thunderstorm. U.S. Government Printing Office, Washington, D.C., 287 pp.

Chisholm, A. J., 1973: Alberta hailstorms, Part I: Radar case studies and airflow models. Meteor. Monogr., 14, Boston, Amer. Meteor. Soc., 1-36.

__________, and J. H. Renick, 1972: The kinematics of multicell and supercell Alberta hailstorms. Research Council of Alberta, Hail Studies Report 72-2, 24-31.

Donaldson, R. J., Jr., R. M. Dyer, and M. J. Kraus, 1975a: Operational benefits of meteorological Doppler radar. AFCRL, Air Force Surveys in Geophysics, No. 301, 26 pp.

__________, __________, __________, 1975b: An objective evaluator of techniques for predicting severe weather events. Preprints, 9th Conf. on Severe Local Storms, Boston, Amer. Meteor. Soc., 321-326.

Doswell, C. A., III, 1977: Obtaining meteorologically significant surface divergence fields through the filtering property of objective analysis. Mon. Wea. Rev., 105 [In Press].

Foster, D. S., 1976: Verification of severe local storm warnings based on radar echo characteristics. NOAA Tech. Memo. NWS TDL-60, Silver Spring, Techniques Development Lab, 10 pp.

Fujita, T. T., and H. Grandoso, 1968: Split of thunderstorm into anticyclonic and cyclonic storms and their motion as determined from numerical model experiments. J. Atmos. Sci., 25, 416-439.

Hamilton, R. E., 1969: A review of use of radar in detection of tornadoes and hail. ESSA Tech. Memo. WBTM-ER-34, Garden City, New York, Weather Bureau Eastern Region, 64 pp.

Hart, H. E., and L. W. Cooper, 1968: Thunderstorm airflow studies using radar transponders and super-pressure balloons. Preprints, 13th Weather Radar Conf., Boston, Amer. Meteor. Soc., 196-201.

Lemon, L. R., 1970: Formation and emergence of an anticyclonic eddy within a severe thunderstorm as revealed by radar and surface data. Preprints, 14th Conf. on Radar Meteor., Boston, Amer. Meteor. Soc., 323-328.

__________, 1976a: The flanking line, a severe thunderstorm intensification source. J. Atmos. Sci., 33, 686-694.

__________, 1976b: Wake vortex structure and aerodynamic origin in severe thunderstorms. J. Atmos. Sci., 33, 678-685.

__________, 1976c: Tornadic storm evolution: Vortex valve hypothesis. Appendix F, The Union City, Oklahoma tornado of 24 May 1973. R. A. Brown, Ed. NOAA Tech. Memo. ERL NSSL-80, Norman, National Severe Storms Lab, 229-234.

__________, 1977: Severe thunderstorm evolution: Its use in a new technique for radar warnings. Preprints, 10th Conf. on Severe Local Storms, Boston, Amer. Meteor. Soc.

__________, D. W. Burgess, 1976: Tornadic storm airflow and morphology derived from single Doppler radar measurements. Chapter 8, The Union City, Oklahoma tornado of 24 May 1973. R. A. Brown, Ed. NOAA Tech. Memo. ERL NSSL-80, Norman, National Severe Storms Lab.

__________, __________, and R. A. Brown, 1975: Tornado production and storm sustenance. Preprints, 9th Conf. on Severe Local Storms, Boston, Amer. Meteor. Soc., 100-104.

__________, R. J. Donaldson, Jr., D. W. Burgess, and R. A. Brown, 1977: Doppler radar application to severe thunderstorm study and potential real-time warning. Bull. Amer. Meteor. Soc. [Submitted for publication]

Marwitz, J. D., 1971: Supercell storms and the Soviet hailstorm model. Preprints, International Wea. Mod. Conf., Geneva.

__________, 1972a: The structure and motion of severe hailstorms. Part I: Supercell storms. J. Appl. Meteor., 11, 166-179.

__________, 1972b: The structure and motion of severe hailstorms. Part II: Multicell storms. J. Appl. Meteor., 11, 180-188.

__________, 1972c: The structure and motion of severe hailstorms. Part III: Severely sheared storms. J. Appl. Meteor., 11, 189-201.

__________, 1973: Trajectories within the weak echo regions of hailstorms. J. Appl. Meteor., 12, 1174-1182.

__________, and E. X. Berry, 1971: The airflow within the weak echo region of an Alberta hailstorm. J. Appl. Meteor., 10, 487-492.

Nelson, S. P., 1976: Characteristics of multicell and supercell hailstorms in Oklahoma. Preprints, International Conf. on Cloud Physics, Boulder, Colorado, 335-340.

__________, 1977: Rear flank downdraft: A hailstorm intensification mechanism. Preprints, 10th Conf. on Severe Local Storms, Boston, Amer. Meteor. Soc.

Sulakvelidze, G. K., H. Sh. Biblashvili, and V. F. Lapcheva, 1967: Formation of precipitation and modification of hail processes. Translated by Israel Program for Scientific Translations, Jerusalem, 208 pp.

Sumers, P. W., 1972: Project hailstop: A review of accomplishments to date in Alberta hail studies 1972. Research Council of Alberta, Hail Studies Report 72-2, 47-53.

Williams, R. J., 1976: Surface parameters associated with tornadoes. Mon. Wea. Rev., 104, 540-545.

10. APPENDIX
19 April 1972 Storms

The following storm examples, with brief discussions, are included for examination, primarily by those who are required to interpret the radar display for warning issuance. As in section 5, the techniques and storm radar echo signatures discussed earlier are exemplified. The data are presented in the same manner as in the example in section 5 and were also obtained from the NSSL WSR-57 radar.

The first five storms, examined from 1440 through 1814, occurred across western and central Oklahoma, accompanied by several forms of severe weather including tornadoes, large hail and damaging straight winds as is discussed. The echo identified initially as D split as described in section 5.4, and its history is shown in Fig. 6. In this case, the northern or left moving storm (DL) moved from 211° at 28 m s^{-1} (54 kt) and the right moving storm (DR) moved from 265° at 13 m s^{-1} (25 kt). The storms D, DL, and primarily DR have been examined in detail by Brown *et al.* (1973), Burgess and Brown (1973) and Burgess (1974). Note the relationship of the echo top in storm DR to tornado production in Fig. 7.

On 19 April 1972 the range marks were 20 nmi, the initial range delay was 12 nmi, and the integrator gate size was 2 km (1 nmi). The integrated log reflectivity film levels were set as follows:

Level		Intensity, dBZ
1	Gray	10-19
2	White	20-29
3	Black	30-39
4	Gray	40-49
5	White	50-59
6	Black	$\geq$ 60

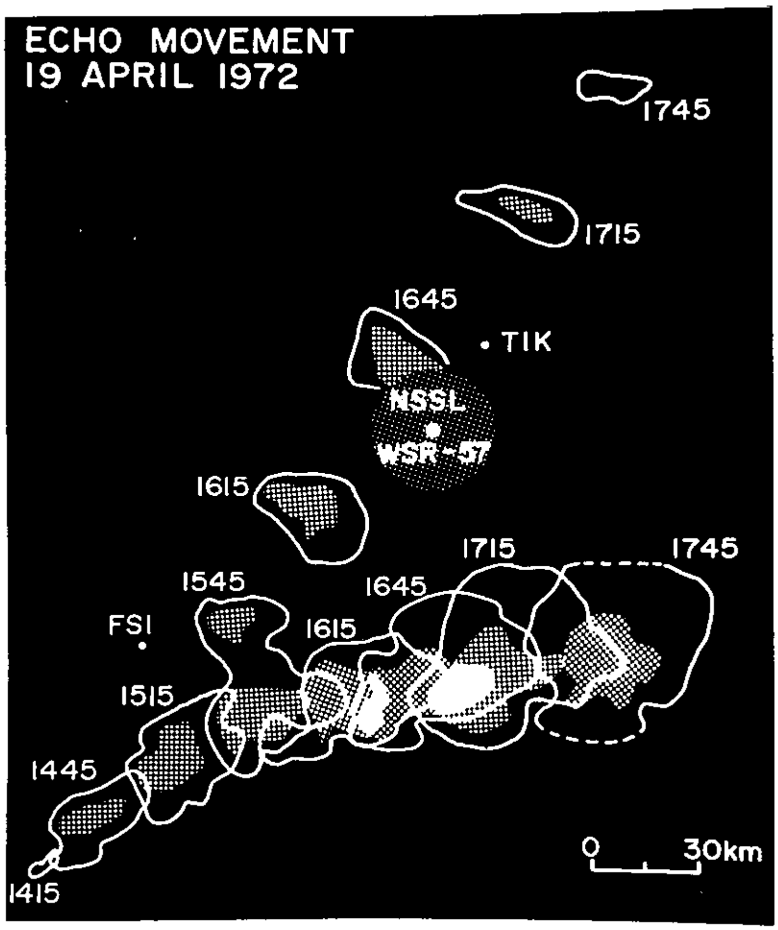


Figure 6. WSR-57 surface radar echo history of storm D, which split into DR and DL. The solid contours indicate return greater than 10 dBZ and the stippled region is return greater than 40 dBZ. The time in CST of each echo position is also indicated (from Burgess, 1974).

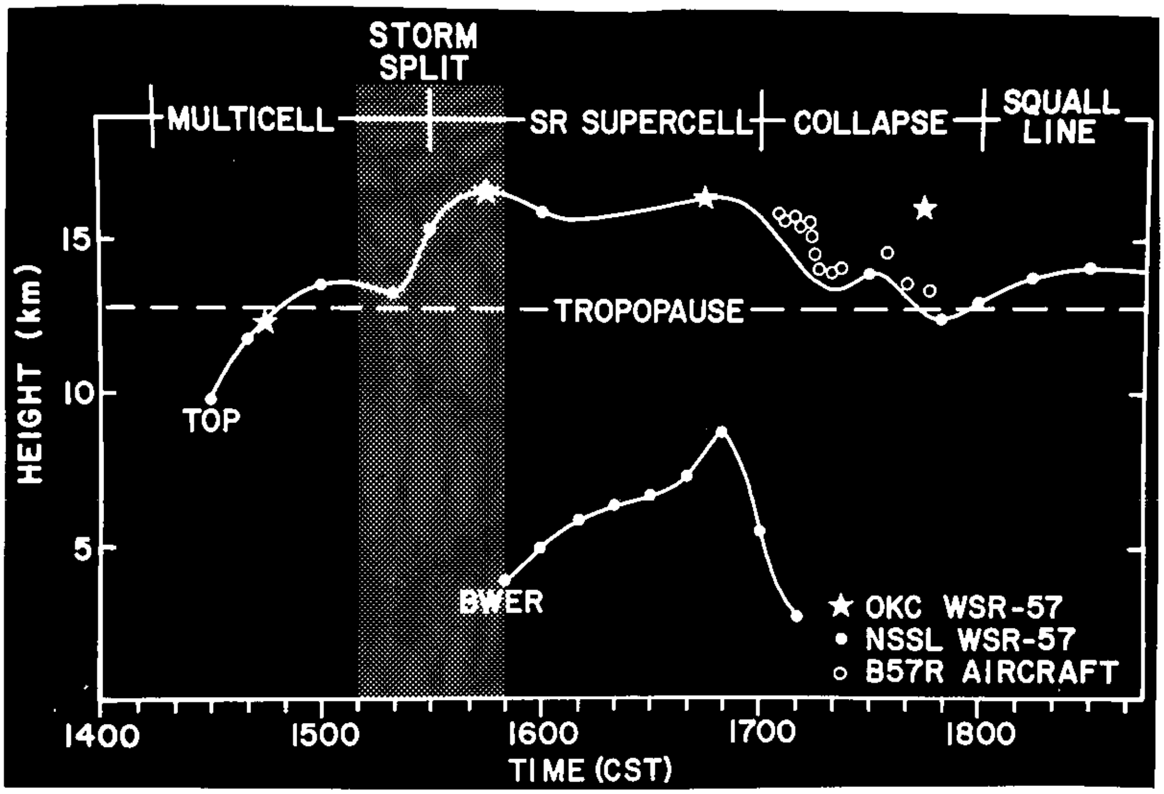
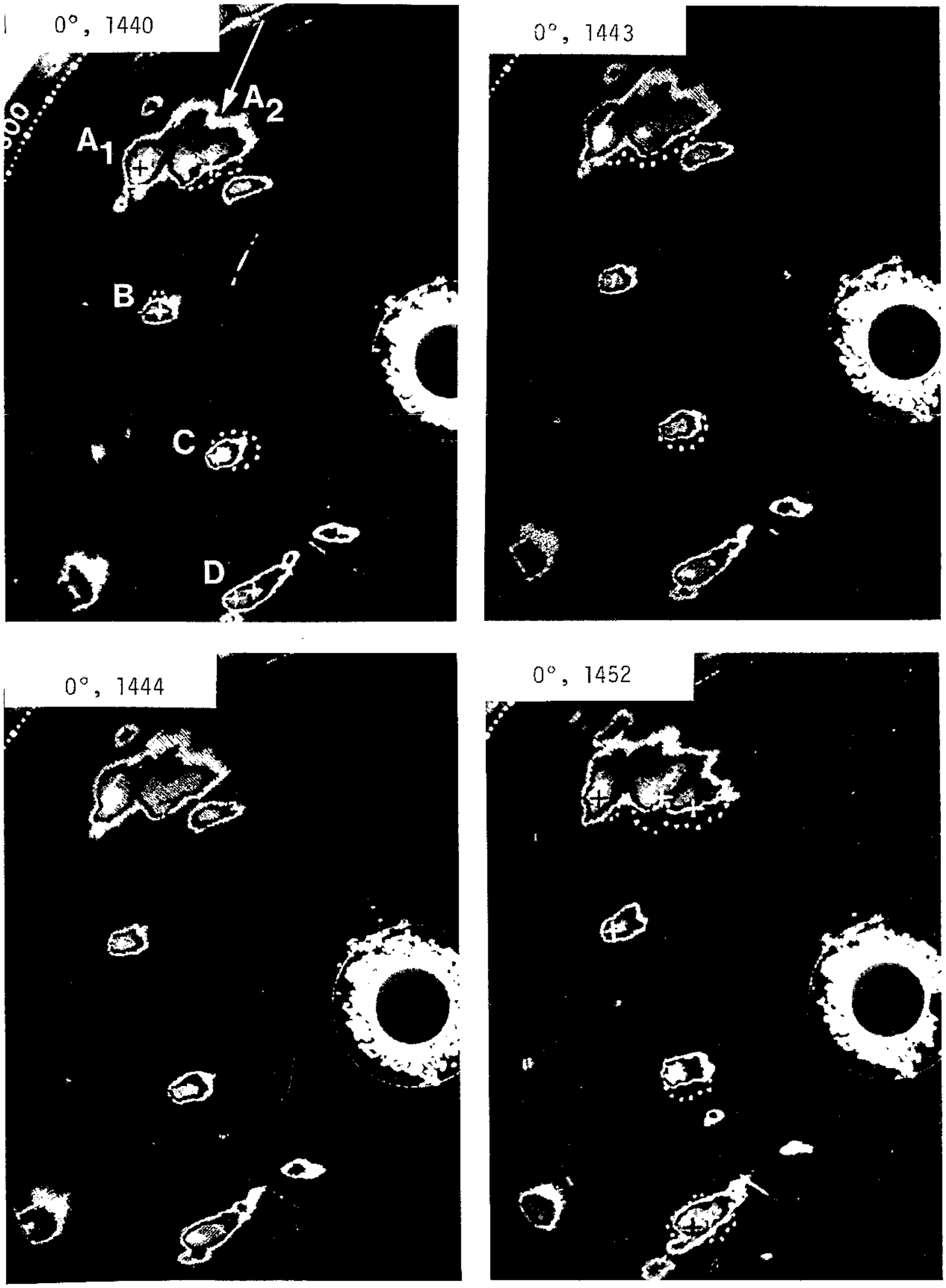
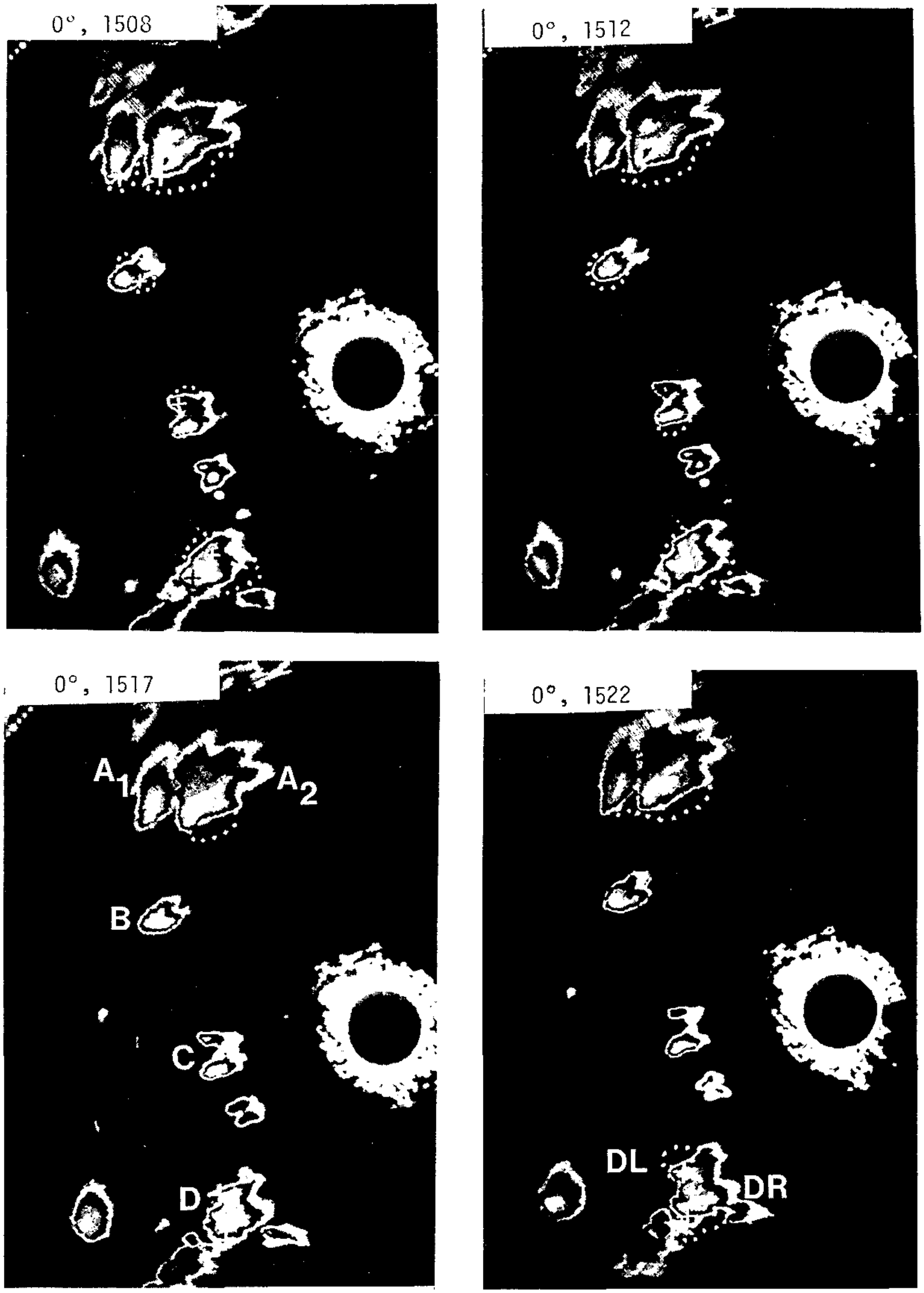


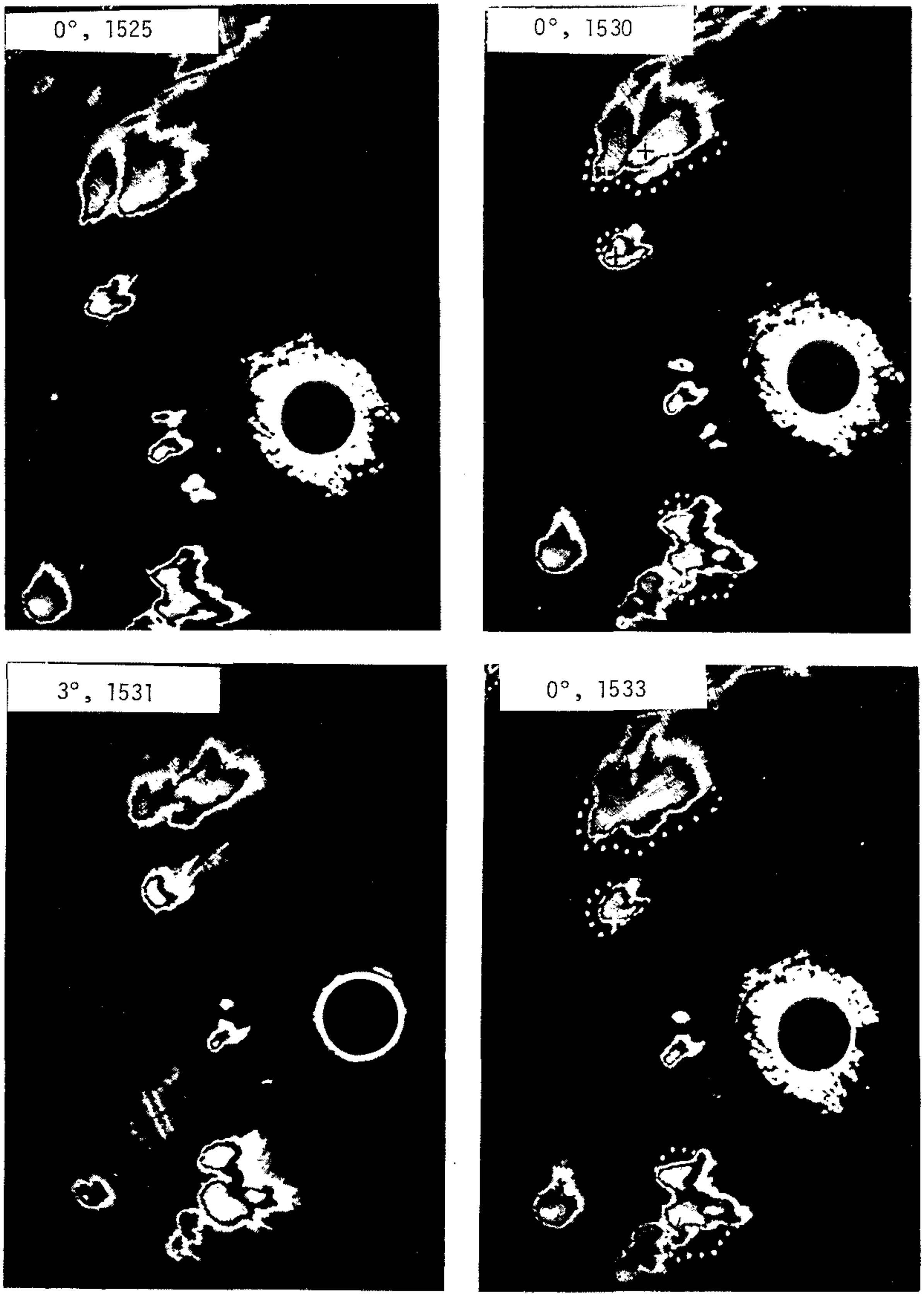
Figure 7. Graph of echo and BWER top with respect to time for storm DR. Stippling indicates the period of storm split (see Figure 6). The tornadoes (five in number) occurred from 1658 to 1735. The last wind damage occurred between 1740 and 1745 (from Burgess, 1974).

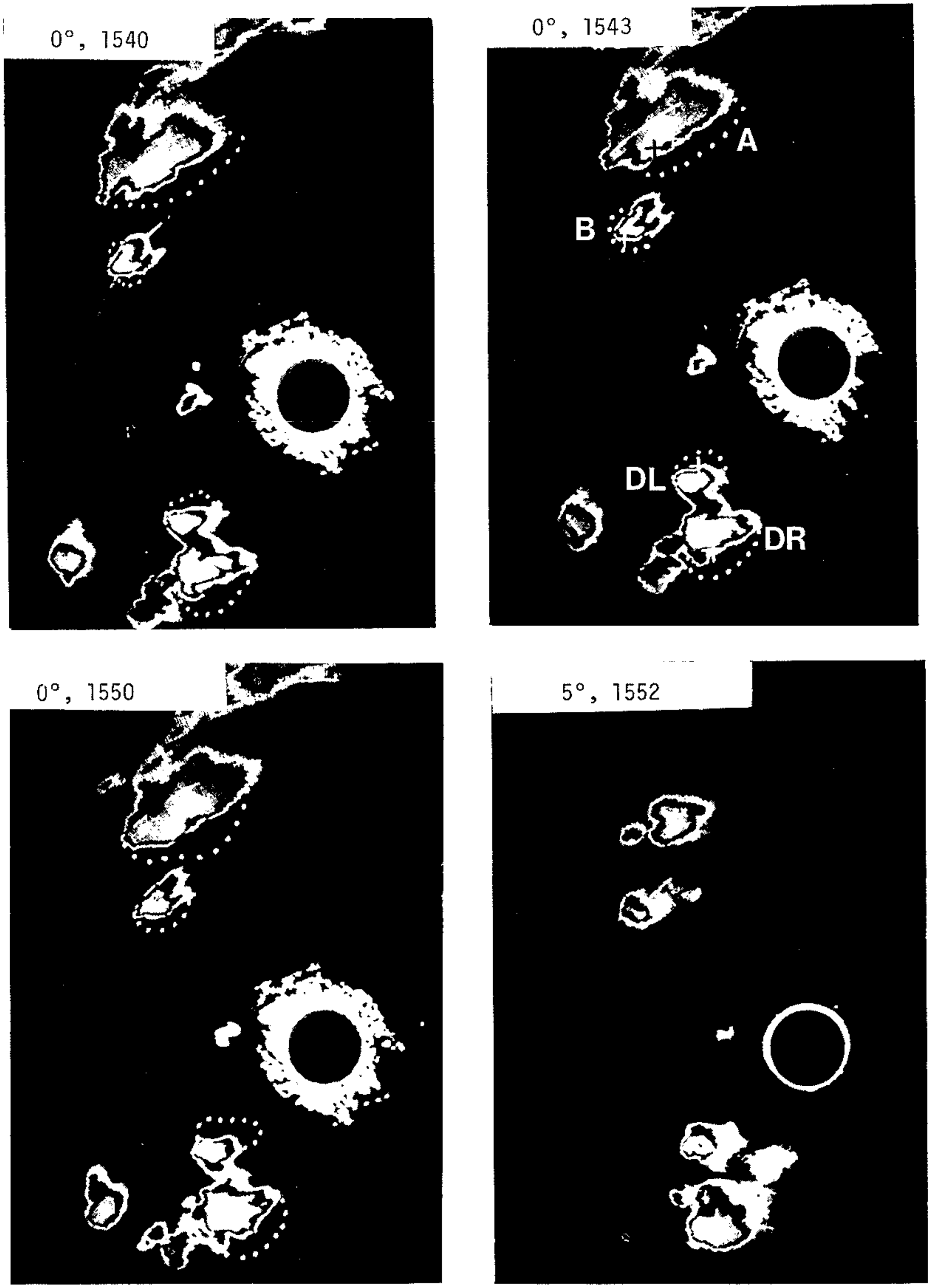
We assume the first view of the radar scope by the weather radar specialist reveals the echo distribution at 1440 and 0° antenna elevation. While in this case the weather radar specialist would be aware that weather conditions are favorable for the development of severe storms, this is not necessary for use of these techniques.

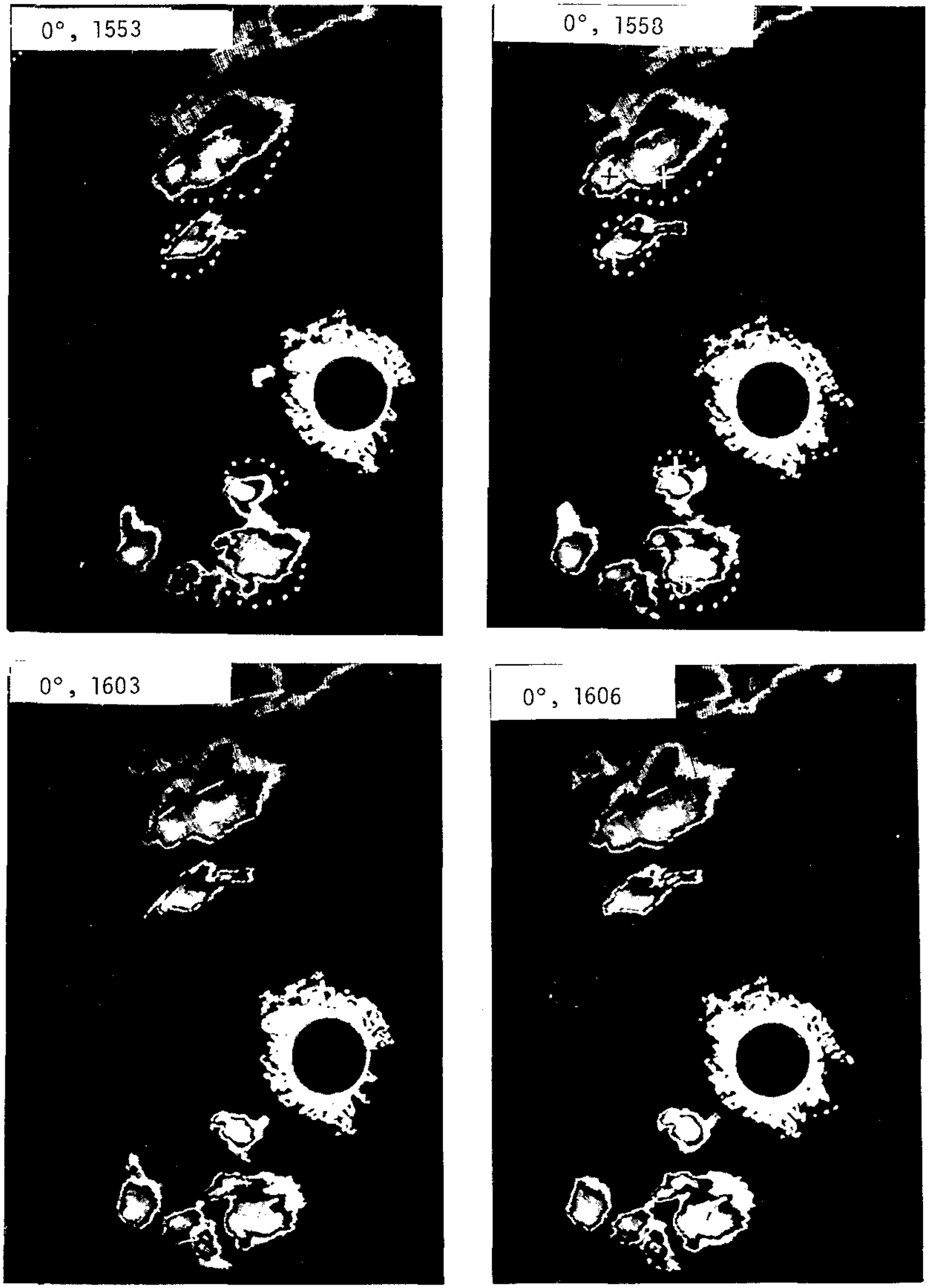
A widely scattered line of storms is present to the west. Because of the echo distribution, nearly every storm present has little competition for low-level inflow and is a candidate for severe development. The largest, most intense storms are A_1 and A_2. A_2 has a downwind "V notch" structure (arrow) as well as the other structures explained in the discussion following the illustrations.

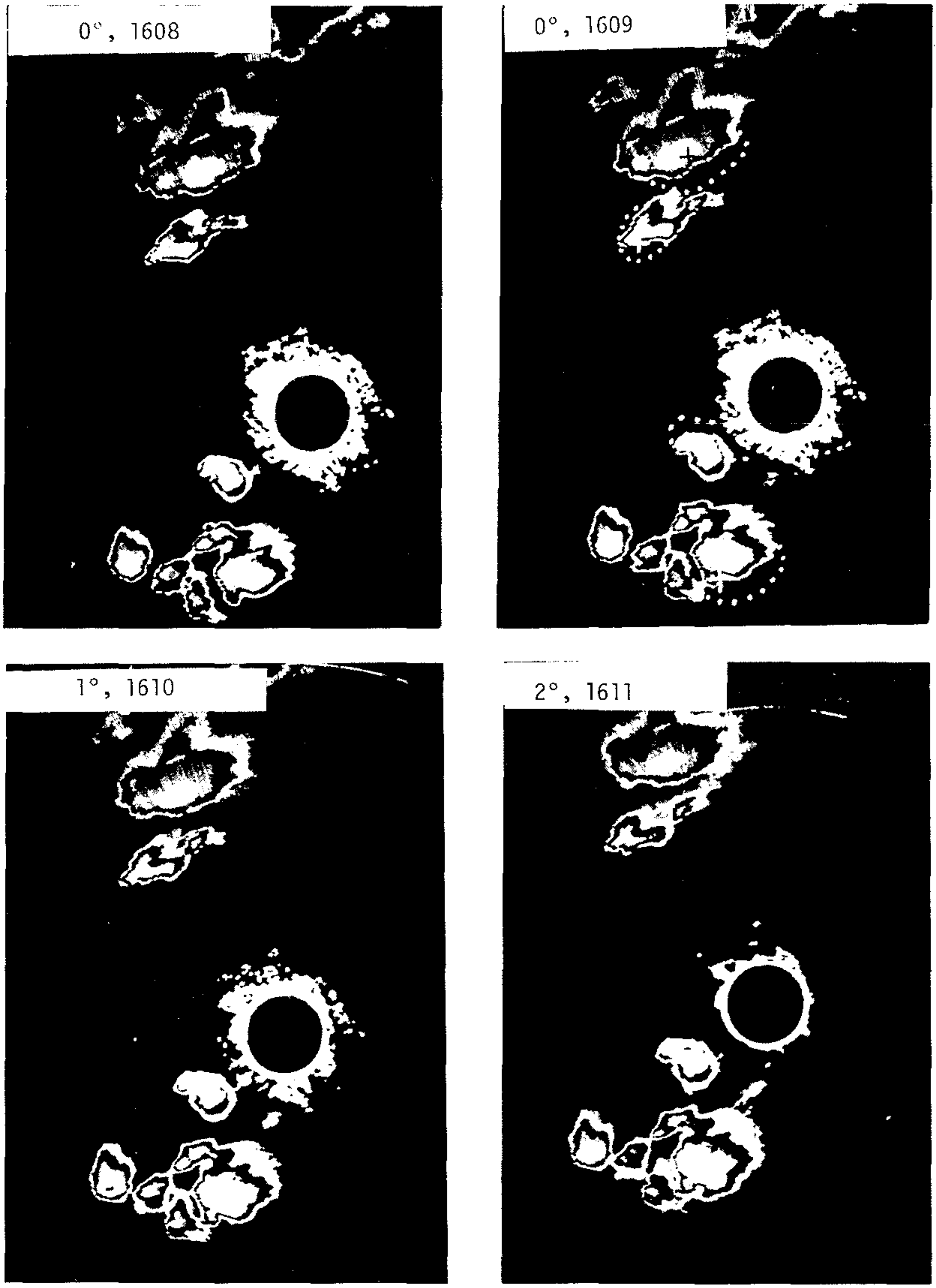

0°, 1440
A1
A2
B
C
D
0°, 1443
0°, 1444
0°, 1452

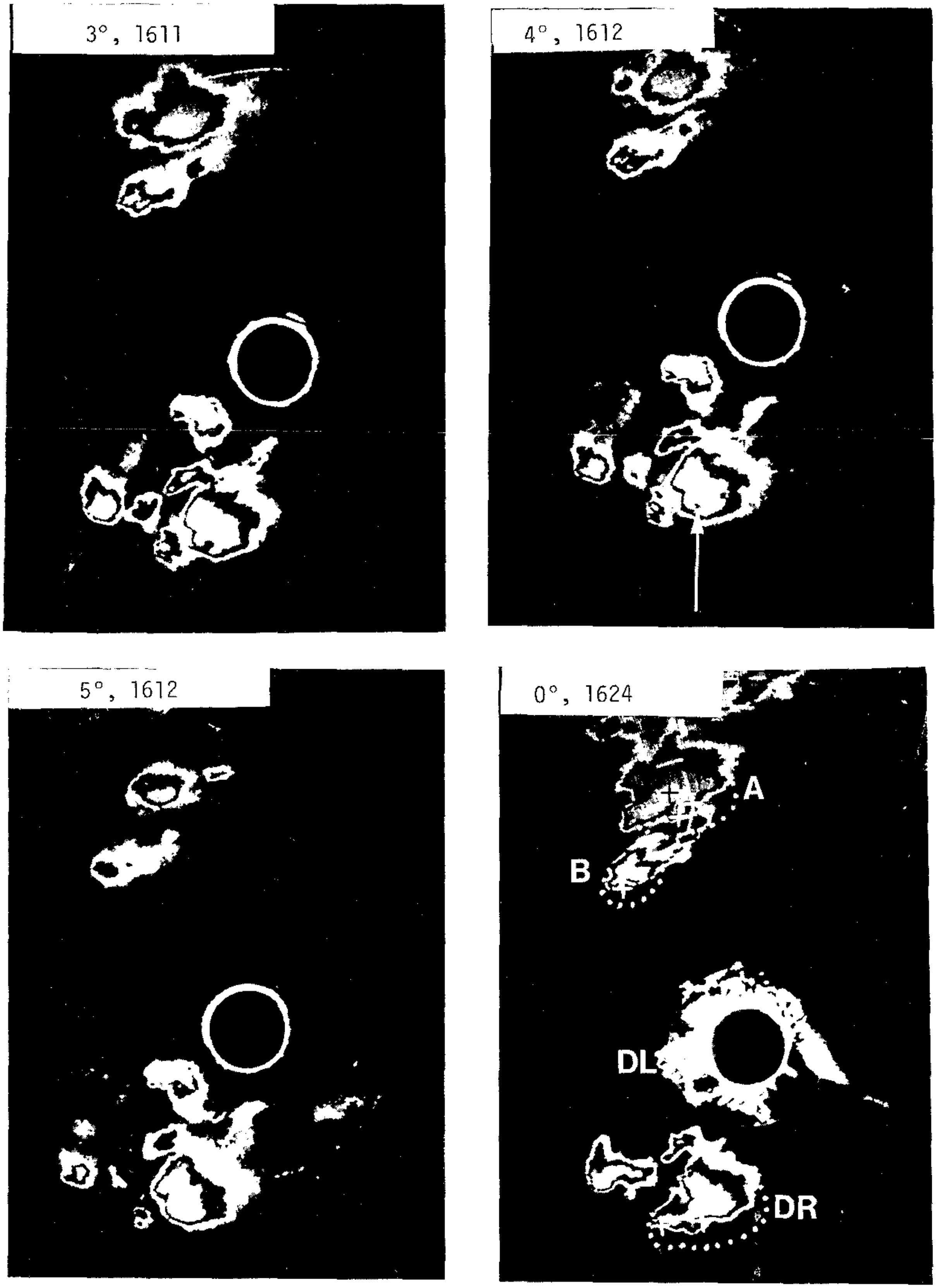

0°, 1508
0°, 1512
0°, 1517
A1
A2
B
C
D
0°, 1522
DL
DR

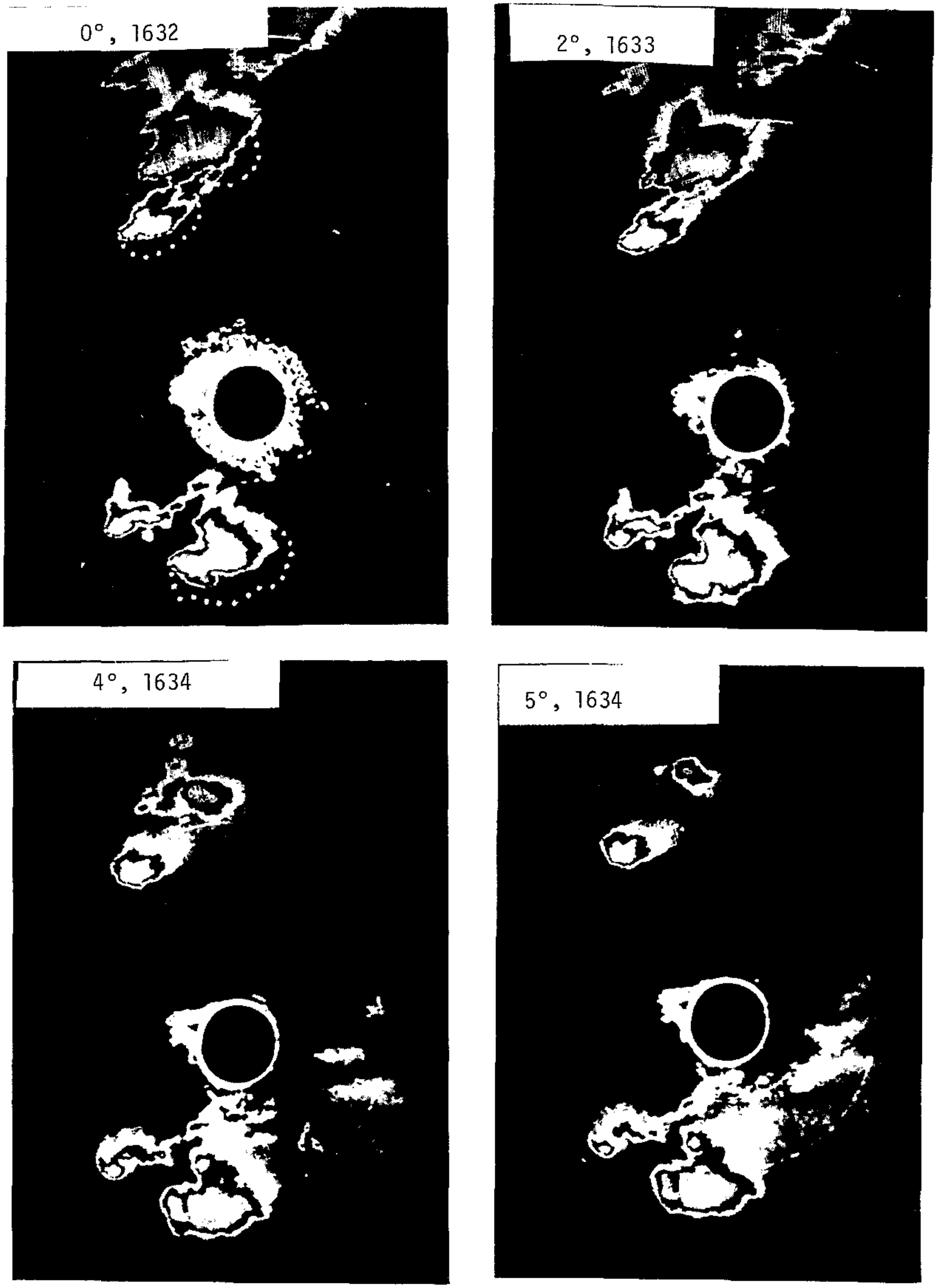

0°, 1525
0°, 1530
3°, 1531
0°, 1533

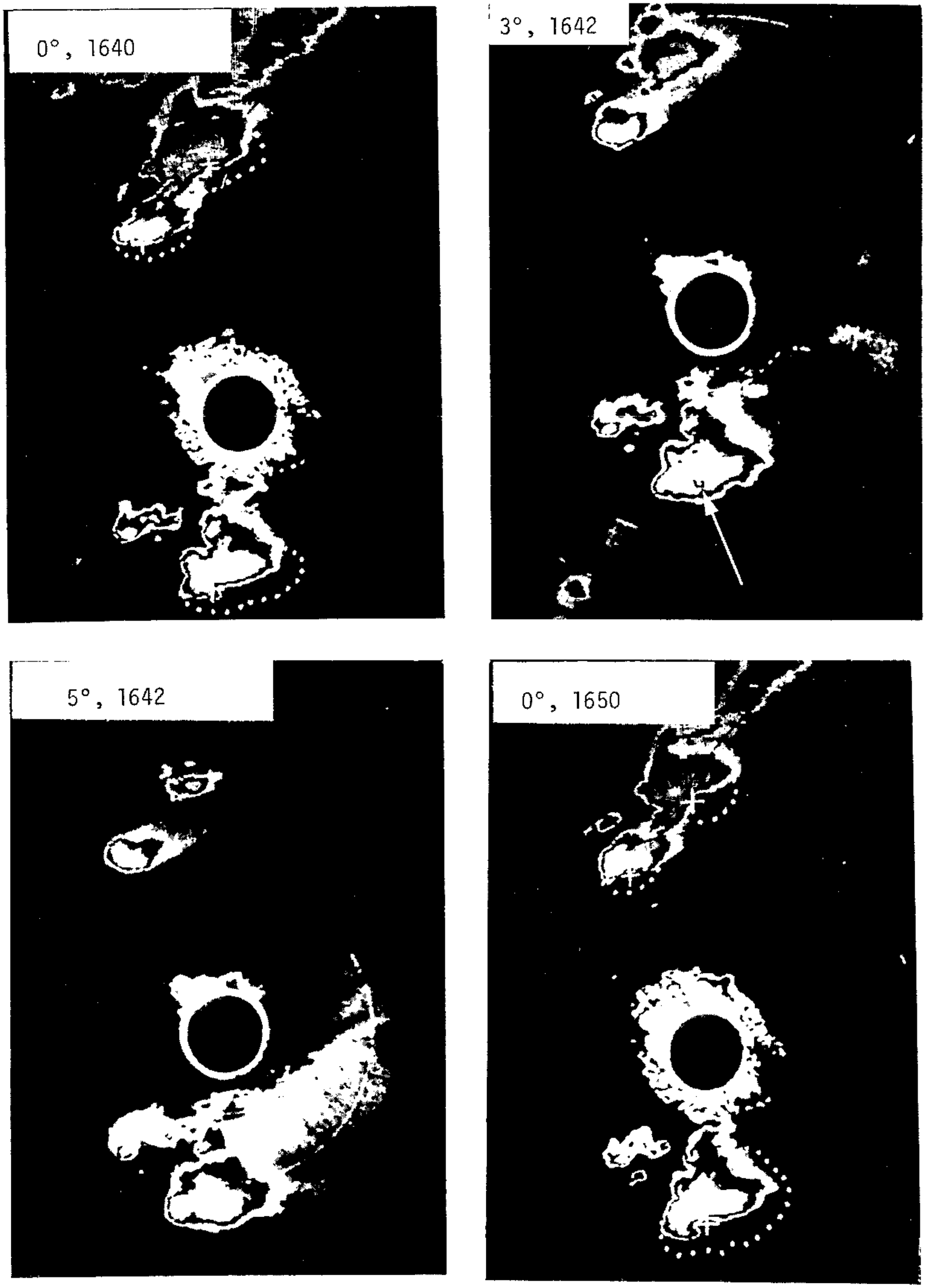

0°, 1540
0°, 1543
A
B
DL
DR
0°, 1550
5°, 1552

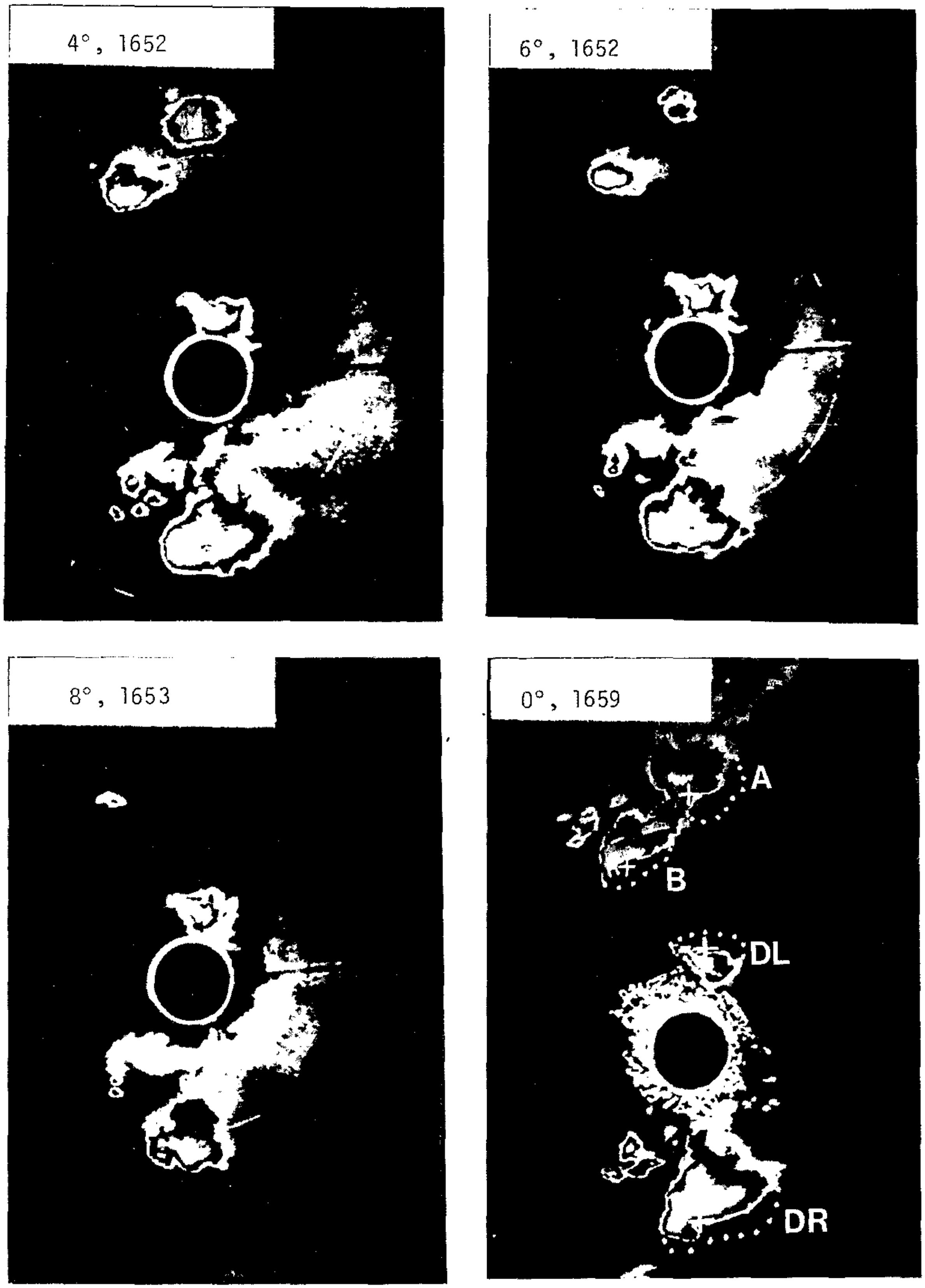

0°, 1553
0°, 1558
0°, 1603
0°, 1606

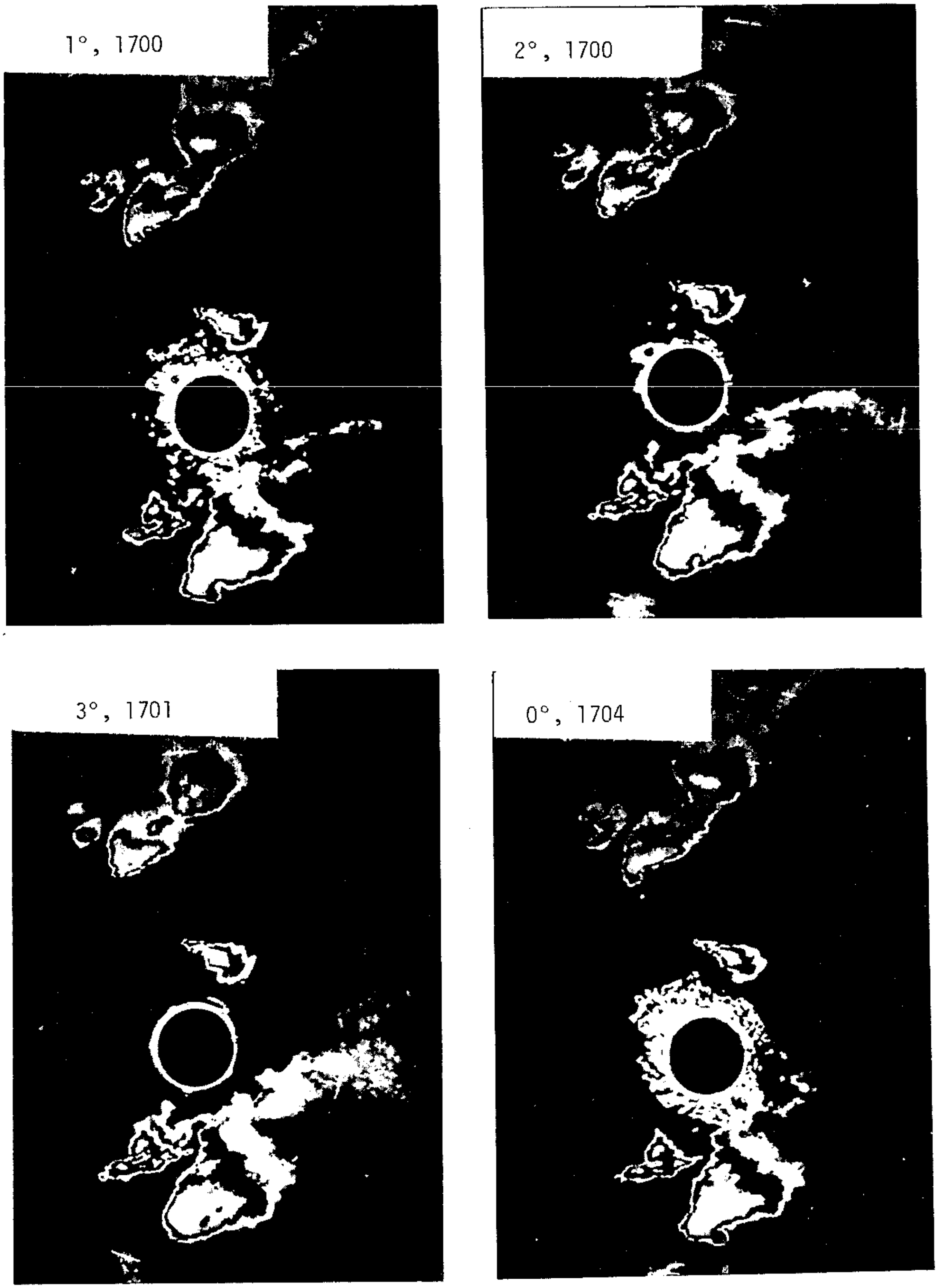

0°, 1608
0°, 1609
1°, 1610
2°, 1611


3°, 1611
4°, 1612
5°, 1612
0°, 1624
A
B
DL
DR

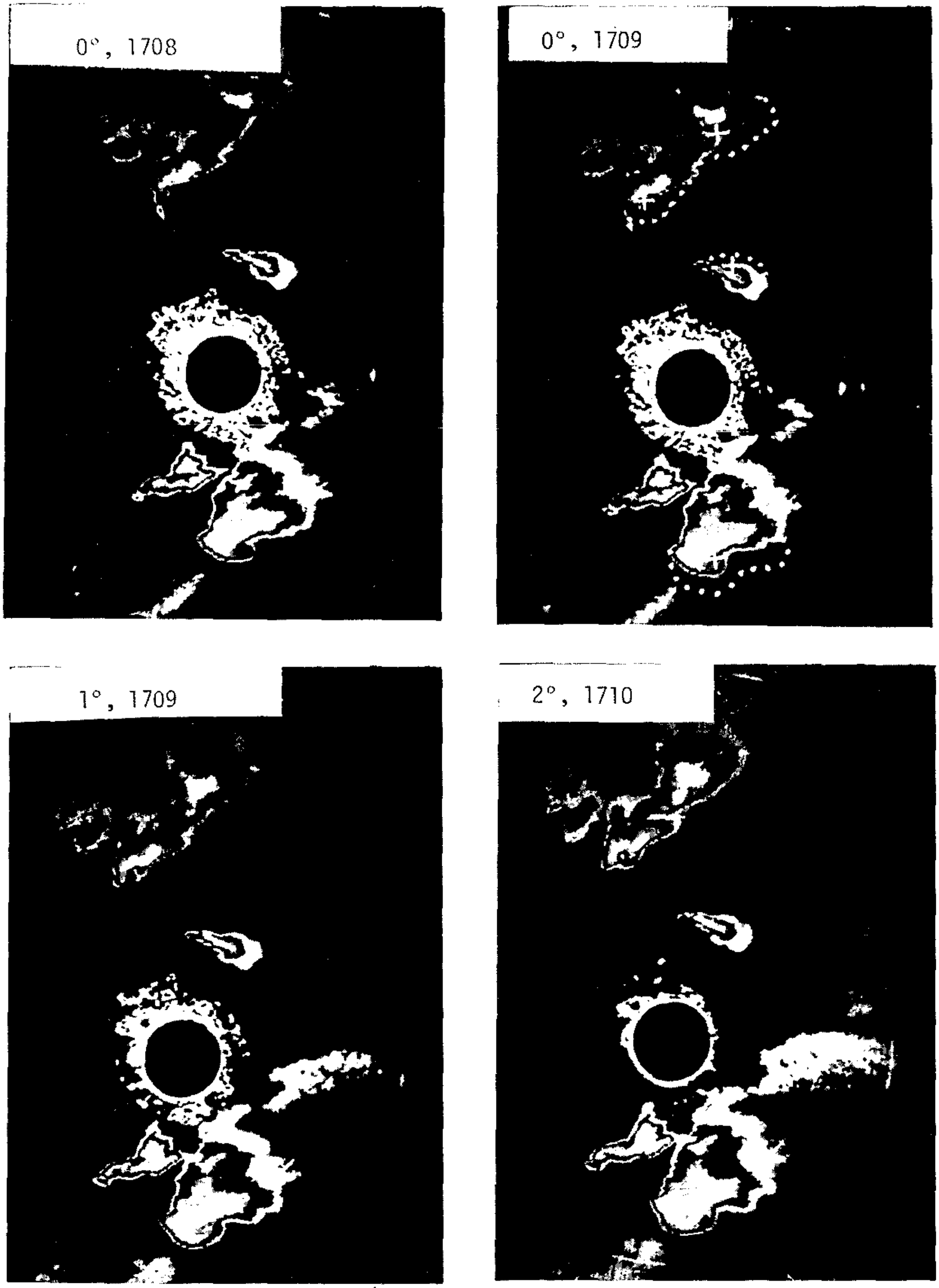

0°, 1632
2°, 1633
4°, 1634
5°, 1634

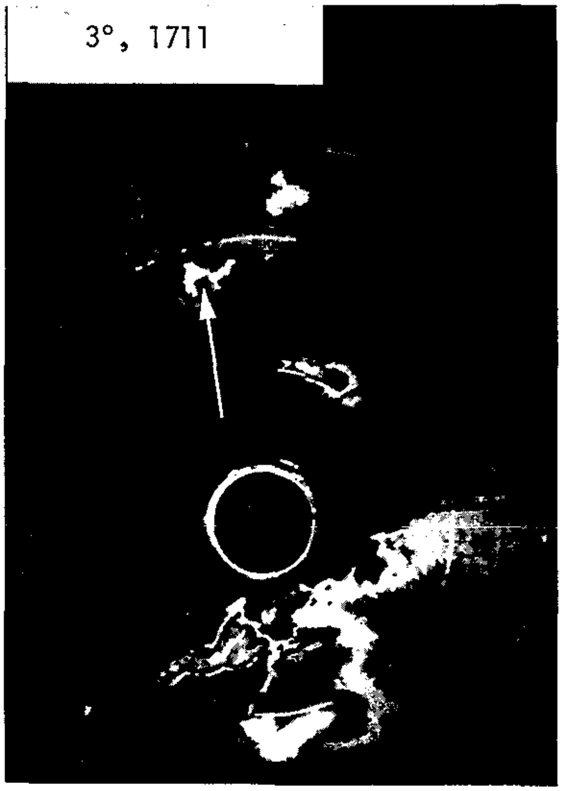

0°, 1640
3°, 1642
5°, 1642
0°, 1650


4°, 1652
6°, 1652
8°, 1653
0°, 1659
A
B
DL
DR



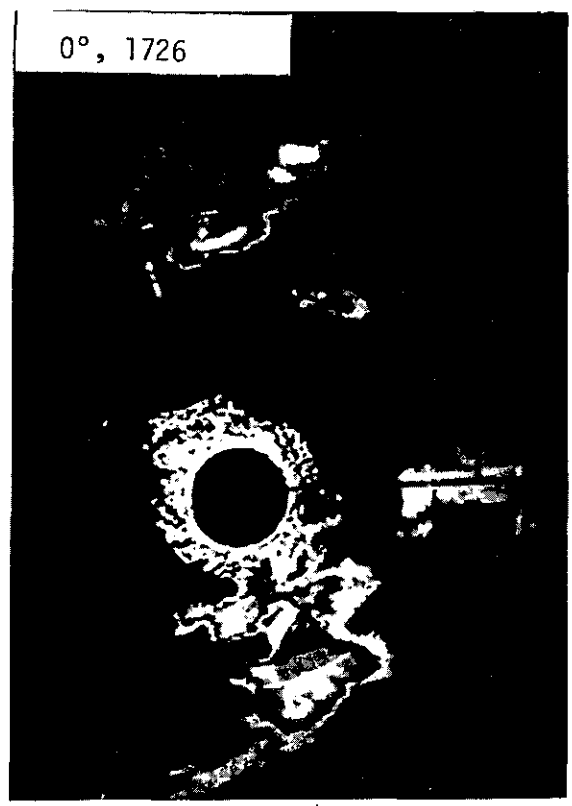
1°, 1700
2°, 1700
3°, 1701
0°, 1704

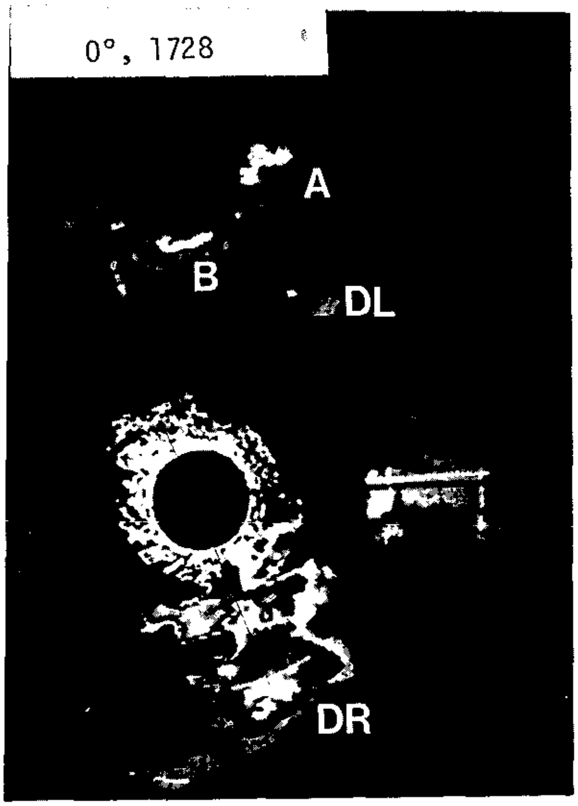

0°, 1708
0°, 1709
1°, 1709
2°, 1710

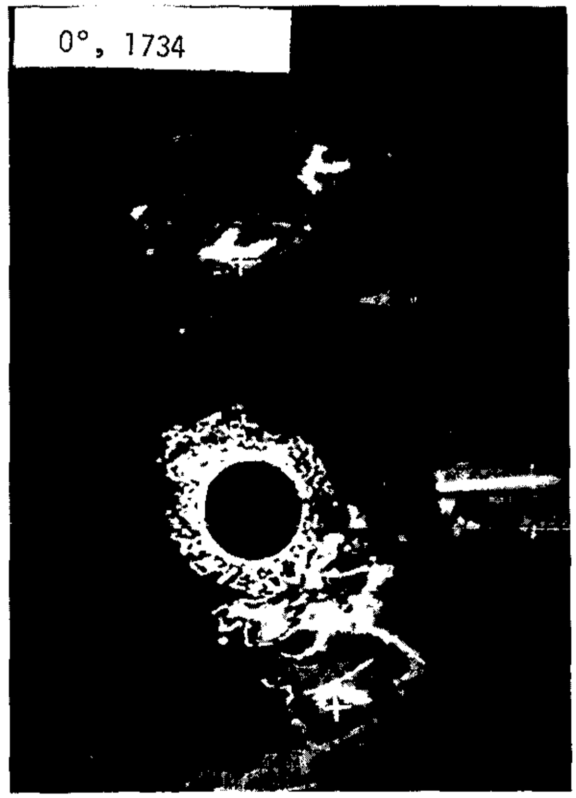

3°, 1711


0°, 1714

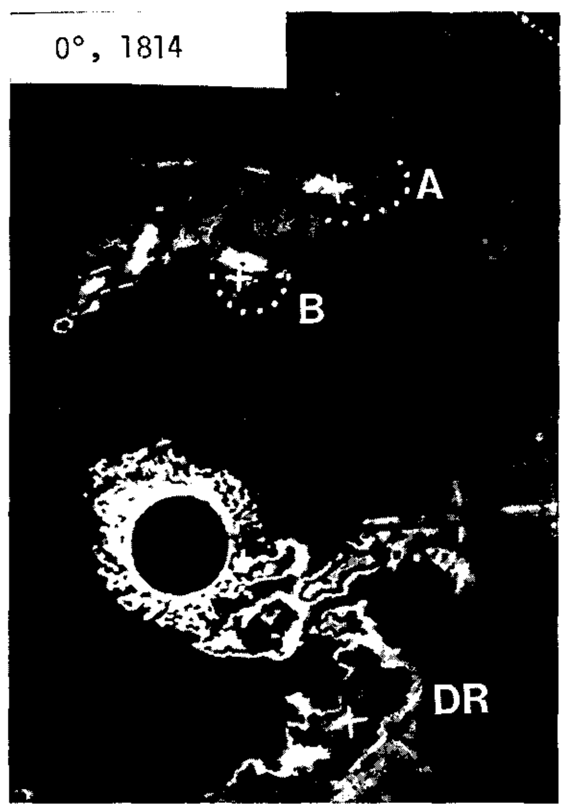

0°, 1720


0°, 1726


0°, 1728
A
B
DL
DR


0°, 1734


0°, 1745


0°, 1814
A
B
DR

0°, 1440

A_1 - This multicell storm (two echo tops, one indicated in black, the other white) is found to exhibit no overhang in the following tilt sequence and so would be considered nonsevere. The mean environmental winds are 240° at 27 m s^{-1} (52 kt). A_1 movement is from 242° at 16 m s^{-1} (32 kt).

A_2 - Although two echo tops exist (one has been omitted from the photograph), they are over the edge of the inflow low-level echo flank and are associated with an 8 km (4 nmi) overhang. The westernmost top (not shown) is associated with and just to the east of the pendant in the fourth level echo. A tornado warning is issued in this simulated real-time evaluation at the completion of the tilt sequence following 1440 (valid 1443-1540). (Later information confirmed that a tornado and large hail were in progress at this time.) Storm movement is from 250° at 18 m s^{-1} (35 kt).

B - The echo top is found over the core and there is little mid-level echo overhang; therefore, this storm is nonsevere. Movement is 236° at 18 m s^{-1} (35 kt).

C - Most overhang is on the downwind (forward) storm flank and the echo top is nearly over the middle of the storm core. Again, this storm is nonsevere. Its movement is 230° at 18 m s^{-1} (35 kt).

D - This is a multicell storm with the tops over the cores and no overhang. The nonsevere storm is moving from 229° at 12 m s^{-1} (23 kt).

0°, 1443

A_1 and A_2 - The tilt sequence has just been completed and warnings issued. The pendant with A_2 continues to wrap up. The echo top is located at the east edge of the fourth level pendant.

B - No change.

C - Although overhang now exists on the right flank and reflectivities at 5.5 km (18,000 ft) are fifth level, the top is still over the core and the storm is, therefore, nonsevere but should be watched for echo top shift.

D - Very rapid development is occurring (fifth level cores have formed in 3 min) but the same nonsevere structure remains.

0°, 1444

A_1 - No change.

A_2 - The hook continues to wrap up as the fifth level storm core has dissipated. (The observed tornado dissipates at 1450.)

B, C, D - Little change is occurring in these storms.

0°, 1452

A_1 - No appreciable change except that the storm now appears single cellular (one echo top).

A_2 - The hook has wrapped up and is no longer detectable. The top, that was in association with the pendant, is included here. The smaller echo to the south has merged with A_2, but the overhang persists and the storm still has the severe structure.

B, C, D - Again, little change has occurred.

0°, 1508

A_1 - A small (~ 3 km, 1.6 nmi) overhang has developed and the top is shifting toward the inflow flank. The storm should be watched closely.

A_2 - The storm has intensified greatly with reflectivities now greater than 60 dBZ. The overhang has expanded to 11 km (6 nmi).

B - A small overhang (4 km, 2 nmi) exists on both flanks. The echo overhang to the right and the associated echo top is produced by a new cell developing aloft. The storm is still nonsevere.

C - Although this storm is splitting, the structure of both cells is still nonsevere.

D - The storm has grown in size and strength, but most of the overhang is on the downwind flank. Storm tops also remain over the echo interior and the storm remains nonsevere.

0°, 1512

A_1 through D - No appreciable change in any storms.

0°, 1517

A_1 - No change has occurred.

A_2 - The fifth level core has begun to swing southward developing a pendant echo and the top is again just to the east of the pendant. Another tornado appears probable. (Although no verified tornado occurred, 1.3 cm (.5 inch) to 9 cm (3.5 inch) hail and funnel clouds were reported from 1520 to 1550.)

B - No appreciable change has taken place.

C - The storm has essentially split, but both cells have nonsevere structures.

D - Insufficient mid-level data were obtained here, but the shift in echo tops (included here) suggests that the storm is splitting and becoming severe.

0°, 1522

A_1 - The echo has weakened somewhat.

A_2 - Little change is occurring except that the echo top has apparently decreased from about 16.5 km (54,000 ft) to about 15.6 km (51,000 ft) adding confidence to the tornado warning.

B - Although the low-level echo has strengthened, developing a fifth level core, no appreciable overhang nor a shift in the echo top has occurred and the storm is interpreted as nonsevere.

C - Both of the split cells continue to weaken and are not discussed further.

D - The southern counterpart of the splitting storm (labeled DR hereafter) begins deviating 25° to the right (265°, 13 m s^{-1}, 25 kt) of the mean winds. It has developed a 6 km overhang, mid-level intensity greater than 50 dBZ, with the major echo top shifted (and shown here) and a severe thunderstorm warning is issued (1525-1625). The northern storm, referred to as DL, begins moving 29° left of the mean winds and faster (211° at 28 m s^{-1}, 54 kt). The echo top location (also shown) leaves some doubt as to the severe character and a warning is not yet issued.

0°, 1525

No tilt data were obtained at this time. The wrap up of the fifth level pendant continues in storm A_2, but other storms cannot be further evaluated.

0°, 1530

A_1 - Although a small overhang is present, weakening echo strength continues and the top remains over the core.

A_2 - The maximum echo top has now shifted to over the core, overhang has decreased and wrap up is complete. A second developing top is over the inflow flank. Small second level calls (beneath the overhang) developing on the right flank comprise a "flanking line" of developing, towering cumulus merging with the collapsing supercell (see Lemon, 1976a).

B - The storm still has the nonsevere structure, but a rapid increase in strength of mid-level echo is occurring.

DL - The top has shifted and based on the severe structure, a warning is issued (valid 1530-1630).

DR - The storm has developed an obvious pendant echo and a 10 km (5.4 nmi) overhang. The echo top associated with the supercell is located above the pendant. A tornado warning is issued (valid 1530-1630). (Hail 1.3 to 2.5 cm, .5 to 1.0 inch, in diameter, 33 m s^{-1}, 65 kt, winds and funnel clouds were produced from about this time until 1600.)

3°, 1531

The large, intense mid-level (6 to 8 km, 20,000 to 26,000 ft) echoes of A_2, B, DL, and DR are obviously the most significant.

0°, 1533

A_1 - A new updraft along the rear flank has developed some overhang. The storm should be watched for future development.

A_2 - The "flanking line" cells have been engulfed in the third level echo of A_2 which is maintaining a severe multicell storm structure.

B - Overhang (6 km, 3.2 nmi) with mid-level reflectivities of fifth level has developed along the left rear and right rear echo flanks. The top has shifted (as shown) and a severe thunderstorm warning was issued (valid 1535-1635).

DL, DR - No significant change is occurring.

0°, 1540

A - Cells A_1 and A_2 have sufficiently merged so that the storm as a whole is referred to as A. The storm is multicell as a result of the "flanking line" cell mergers and the fifth level core has extended southward as those cells grow. The echo overhang has increased (to 11 km, 6 nmi). The tornado warning, which is expiring, is reissued as a severe thunderstorm warning (valid 1540-1640).

B - Although overhang has decreased somewhat, the warning is retained.

DL - Little change has occurred.

DR - The overhang has continued to increase (14 km, 7.4 nmi) and a sixth level core has developed aloft (4.6 to 9.0 km, 15,000 to 30,000 ft).

0°, 1543

A, DL, DR - These storms have changed little.

B - Although the fifth level core has dissipated, the severe structure persists and the warning is maintained.

0°, 1550 and 5°, 1552

A - The storm has become a supercell with a pendant echo beginning to develop in the fourth and fifth level contour. The storm top is over the south edge of the low-level echo just east of the pendant. The severe thunderstorm warning is changed to a tornado warning at the completion of the tilt sequence (valid 1553-1650). (Funnel clouds 5 cm, 2 inch, hail and 27 m s^{-1}, 52 kt, winds were beginning to occur.)

B - The echo has strengthened considerably and has a well-developed severe structure.

DL - A sixth level core (difficult to see at 0°) extends from the surface to over 8 km (26,000 ft).

DR - At 9,500 m (31,000 ft) in the 5° scan, a small notch (in the fifth level core) open to the south has developed. This is the initial stage of BWER development.

<u>0°, 1553</u>

A - The wrap up of the pendant is underway.

B, DL, DR - Little change has occurred in these storms.

<u>0°, 1558</u>

A - The wrap up continues which results in a well-developed hook in the fifth level core. The echo top is located over the eastern tip of the hook.

DL - (The first reports of 2.5 cm, 1 inch, hail occur here and continue until about 1700.)

B, DR - There was little change in these storms.

<u>0°, 1603</u> - <u>0°, 1606</u> - <u>0°, 1608</u>

A - The hook wraps up in this series.

B, DL, DR - Little change takes place in these storms.

<u>0°, 1609</u> - <u>1°, 1610</u> - <u>2°, 1611</u> - <u>3°, 1611</u> - <u>4°, 1612</u> - <u>5°, 1612</u>

A, B - The three dimensional structure of both storms is seen. Note the "V notch" on the downwind flank of both storms.

DL - Note the sixth level core aloft (850 to 7,500 m, 2,800 to 24,000 ft). Storm top location cannot be detected because of the small range to the storm and the limited elevation steps used.

DR - The distinct concavity visible on the south flank of the storm at lower levels becomes detectably bounded (BWER, arrow) in the frame at 4° (BWER) at 7.4 km (24,000 ft). At 10.8 km, 35,000 ft or 6° (not shown) the BWER is capped by the fifth level core.

<u>0°, 1624</u>

A - The storm has weakened and become a severe multicell (three echo tops) storm since the supercell collapse.

B - A possible small pendant echo has developed which should be monitored. (Hail of 6.4 cm, 2.5 inches, is reported with the storm about 1630.)

DL - The storm is moving into the ground clutter. Because the storm is inside about 30 km, the technique cannot be used, but based on the structure as it approached the radar, the expiring severe thunderstorm warning is reissued (valid 1630-1730).

DR - Little change has occurred except a new cell and its associated overhang have developed just to the west-southwest of the pendant. The tornado warning which expires at 1630 is reissued (valid 1630-1730).

<u>0°, 1632</u> - <u>2°, 1633</u> - <u>4°, 1634</u> - <u>5°, 1634</u>

A - No change has taken place.

B - The severe thunderstorm warning which expires at 1635 was reissued (valid 1635-1735).

DL - (2.5 cm, 1 inch, hail was reported at this time at the Oklahoma City Weather Service to the northwest of the radar in the ground clutter.)

DR - Developing BWER is seen (2° to 5°) from 3.5 to 8.0 km (11,500 to 26,000 ft).

<u>0°, 1640</u> - <u>3°, 1642</u> - <u>5°, 1642</u>

A - The storm has once again evolved from the multicell to supercell structure, although the low-level echo is not yet well organized. A few much smaller peripheral cells (tops can be seen at 3° and 5°) exist but the large supercell dominates the storm.

B - Little change has occurred.

DL - The storm is still within the ground clutter.

DR - Little change has taken place in the low levels while the BWER (arrow) has become more ovbious at 5.3 km (17,400 ft) with second level surrounded by fourth level or greater echo at 3° elevation angle.

<u>0°, 1650</u> - <u>4°, 1652</u> - <u>6°, 1652</u> - <u>8°, 1653</u>

A - The old warning is expiring, a new severe thunderstorm warning is issued (valid 1650-1750). (A funnel is reported with storm.) From this storm structure, either a tornado or severe thunderstorm warning could have been issued. In this test, only radar information was used in determining when to warn and the type of warning. If the funnel report was used in conjunction with radar storm structure, a tornado warning would have been issued. If the possible pendant becomes better defined or begins to wrap up, a tornado warning should be issued.

B - A pendant has begun to develop and rapidly swing southward. The severe thunderstorm warning is revised to a tornado warning (valid 1650-1750). (Large hail is continuing to fall with the storm.)

DL - The storm is beginning to emerge from the ground clutter.

DR - The well-developed BWER is located directly beneath the storm top shown on the 0° scan and the BWER is seen at 5° and 6° with the capping core at 8°.

<u>0°, 1659</u> - <u>1°, 1700</u> - <u>2°, 1700</u> - <u>3°, 1701</u>

A - No change has occurred in A.

B and DR - A BWER is detected in both but is difficult to discern in the photograph with storm B. The sixth level echo core is just east-northeast of the BWER in DR, 2° to 3°, which is beginning to collapse at this time. (The first two tornadoes are touching down within the pendant of DR.)

DL - The storm still has the severe structure.

<u>0°, 1704</u>

A, B - Storms have undergone little change. No upper level data are shown in these photographs.

DL - The storm is weakening but the severe structure is still present.

DR - The pendant has begun to wrap up. (Giant hail, 7.5 to 10 cm, 3 to 4 inches, begins to fall at this time).

<u>0°, 1708</u>

A, B - Little change has occurred.

DL - Continues to weaken.

DR - Wrap up of the pendant which now takes on curvature (in the fourth level contour) and could be called a hook, is quite apparent.

<u>0°, 1709</u> - <u>1°, 1709</u> - <u>2°, 1710</u> - <u>3°, 1711</u>

A - The supercell structure persists except the low-level core and mid-level overhang are somewhat enlarged.

B - The BWER (arrow at 3°) is better developed. The BWER and storm top are vertically aligned with no slope or tilt which sometimes occurs.

DL - The overhang has decreased considerably.

DR - The remnants of the BWER are encircled by the hook at 1° and 2°.

<u>0°, 1714</u>

A - A second very small fifth level core associated with a smaller cell has developed (arrow).

B - The pendant continues to wrap up.

DL - Weakening of the storm continues.

DR - The hook that was visible in the fourth level core at the 0°, 1709 scan has wrapped up. (The first tornado is dissipating, the second continues, and a third is beginning. Giant hailfall is ceasing.)

<u>0°, 1720</u>

A - The second cell is enlarging resulting in a hook or pendant configuration which is not dynamically significant; i.e., the pendant exists in appearances only as a result of the second cell, but is not a bonafide pendant. The cell top is not shown.

B - The wrap up of the hook continues and the BWER is collapsing.

DL - The storm top has now shifted back over the low-level core and the overhang has dissipated. The severe thunderstorm warning is terminated.

DR - (The second tornado is dissipating.)

<u>0°, 1726</u>

A - Little change has occurred except that the cellular nature of the pendant is more apparent.

B - The wrap up is nearly complete. (A tornado is reported at this time.)

DR - (The third tornado has dissipated and a fourth occurs killing five people. The tornado is located within the swirl or "figure 6" hook in the fifth level core.)

<u>0°, 1728</u>

A - The fifth level core of the second cell is merging with the major fifth level core in such a manner that the configuration of a pendant is again produced but it is again only a configuration and not dynamically significant.

B - The wrap up is nearly complete.

DR - The tornado warning expires at 1730, but is reissued here (valid 1730-1830). The circulation is still quite evident.

0°, 1734

A - Mid-level data are missing and only top data on storms B and DR exist.

B - Wrap up is complete, but the severe structure persists based on top location (over the reflectivity gradient on the south or right flank) and echo overhang as observed during the previous tilt sequence.

DR - (The last tornado just ended, but high wind damage is continuing.)

0°, 1745

A - The cellular structure of the apparent pendant is more easily seen. The warning expires at 1750, but will be reissued as a severe thunderstorm warning (valid 1750-1850).

B - A very small sixth level core has developed. The warning expires at 1750 and will be reissued as a severe thunderstorm warning (valid 1750-1850), but should be watched closely for pendant or BWER development.

DR - The storm top is over the core, the overhang has decreased, and the overall structure is nonsevere. However, storms which have progressed through the supercell evolution collapse stage can still be producing damage and/or tornadoes at this point; therefore, warnings are not terminated.

0°, 1814

A - The overhang is decreasing and has collapsed downward, filling the notch that was present in low levels. The warning is not yet lifted, but may be soon.

B - The storm developed a pendant echo within 10 min after the 0°, 1745 scan, and a tornado warning was issued from 1800 to 1900. Here, the pendant (obscured by top indicator) is wrapping up. (A tornado occurs at about 1825.)

DR - The last indication of internal circulation was 40 min previous. The storm has maintained the nonsevere structure, is part of a line, and weakened; the warning is terminated.